# EFFECTS OF TIMBER HARVESTING ON UPLAND OAK FORESTS IN THE MISSOURI OZARKS

By

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Oak decline-induced mortality and failure of oak regeneration have become a concern in upland oak forests in the Missouri Ozarks. This project investigated the effects of timber harvesting on both oak regeneration and mortality of oak residuals following a suite of timber harvesting treatments in the Missouri Ozarks based on the sixteen-year monitoring data from the Missouri Ozark Forest Ecosystem Project (MOFEP). It indicated that timber harvesting methods impacted the composition and structure of oak reproduction and mortality of oak residuals differently. On dry sites by year 10, clearcutting improved the density of oak reproduction the most, and that intermediate cutting and clearcutting increased the compositional proportion of black oak with 2% and 3%, respectively. Oak mortality was associated with harvesting method, species, diameter, crownclass, basal area in larger trees, and ecological land type. Single-tree selection exacerbated the mortality of residuals, and group selection and no harvesting had a similar effect on oak residuals. Intermediate cutting improved the survival of residuals the most. This project suggested that well-designed silvicultural practices would likely reduce oak decline-induced mortality and increase understory oak reproduction.

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# CHAPTER I

## INTRODUCTION

Oak (*Quercus spp.*) is the most important hardwood in North America for its values and uses (McShea and Healy 2002). Oak ecosystems can provide benefits for forest industry, recreation and aesthetics. White oak (*Q. alba*) has the most valuable rot-resistant wood of all white oaks and thus can be used in making whiskey and wine barrels and for ship-building. While being of less commercial value than white oak, scarlet oak (*Q. coccinea*) is famous for its brilliant autumn color. Wildlife biologists believe that the true value of oak ecosystems is their contribution to the diversity of wildlife in providing habitat and acorns as food resources. Their distribution patterns, amount and dominant overstory trees are exceptionally important to forest wildlife.

In eastern United States, 51% of the forest lands are oak-dominated forests (Spetich et al. 2002, Moser et al. 2006). Among them, the Missouri Ozarks are dominated by contiguous, high-density, upland oak forests. However, since the 1970s, oak decline and mortality has plagued oak-dominated forests in the Ozarks of Missouri and Arkansas at an unprecedented level (Law and Gott 1987). Oak decline will potentially first alter forest structure and species composition, and then wildlife (James 2004, Spetich 2004). The genus *Quercus* contains over 500 species worldwide, but 57 oak species have been threatened with extinction in the eastern United States from 1856 to 1986 (Millers et al. 1989, Oldfield and Eastwood 2007). Seedling scarcity, and lag of regeneration to other forest components make the future of these forests questionable (Moser et al. 2006, Woodall et al. 2008).

In 1989, the Missouri Department of Conservation launched a century-long, ecosystem-scale study in the Ozark Highlands, the Missouri Ozark Forest Ecosystem Project (MOFEP), with a goal of studying the effects of three management systems, even-aged, uneven-aged and no harvest management on the components and structure in the upland oak forest ecosystem. Permanent plots installed on the MOFEP study sites for monitoring important forest ecosystem attributes and components have been measured every three to five years since 1990. The specific objectives of this study are to (1) use the MOFEP data to examine the impact of the three harvest treatments on understory regeneration, and (2) estimate the decline and mortality of the overstory residuals.

The thesis was organized as follows: Chapter II contains the study of oak regeneration, entitled "Effects of Timber Harvesting on the Understory Oak Regeneration in upland Oak Forests in the Missouri Ozarks". In this chapter the changes in species composition and size structure of oak reproduction were characterized. Chapter III describes the study of oak decline and mortality, studied "Effects of Timber Harvesting on the Mortality of Overstory Oak Residuals in Upland Oak Forests in the Missouri Ozarks". The survival times among various treatments were compared; and the underlying distribution of survival time of a single tree and risk factors were modeled. Finally, in Chapter IV are the conclusions of the thesis.

## Chapter II

## EFFECTS OF TIMBER HARVESTING ON THE UNDERSTORY OAK REGENERATION IN UPLAND OAK FORESTS IN THE MISSOURI OZARKS

### Introduction

Oaks have been a dominant group and readily regenerating in eastern deciduous forests for thousands of years (Lorimer 1993). However, on many good or average sites, oak stands harvested in the past 40 years are now dominated to various degrees by other hardwood species (Loftis et al. 1990a). Oak regeneration is a vital process to sustain upland oak forests. Widespread fire suppression and lack of active timber management that regulates overstory are believed to be some of the major causes of oak regeneration failure (Hicks 1998). Oaks are disturbance-dependent species, and disturbances (e.g., logging, fire, wind) are an integral part of oak regeneration and dominance of oak forests (Johnson 2004).

There are three sources of oak regeneration: seedlings, seedling sprouts, and stump sprouts (Johnson 1992). It is difficult to account for all of the influential factors that affect the population dynamics of oak regeneration, but all the factors can be classified as biotic (e.g., herbaceous vegetation, disease, competition and mutualism with plants and animals) or environmental factors (e.g., light, temperature, moisture, nutrients, wind and disturbance regime) of the site (Barnes et al. 1980, Fei and Steiner 2008). Possible causes of oak regeneration problems include poor seed crop, poor initial seedling establishment, climate change, and excessive competition (Lorimer 1993). Establishment is the most critical stage in the life history of an individual oak species. Numerous climatic factors affect the development of oak flowers, such as temperature, humidity, precipitation, wind, and late freezes (Sharp and Chrisman 1961). Flowering leads to acorn production, and oaks produce large seed crops at 2-10 year intervals. Damage to acorns reduces oak regeneration potential. Oaks can produce seed prolifically, but only a small percent (less than 20 percent) of the total crop may be sound and well-developed; the others can be damaged by animals or insects (Myers 1978, Gibson 1982). Among the remaining viable acorns, some of them may fall into unsuitable microsites for germination and establishment. Once acorns are on the ground, desiccation, excessive heat or cold can make them deteriorate quickly. However, seedlings can be produced prolifically during heavy crop years. Even though large numbers of oak seedlings can be established, mortality rates of young seedlings are still high considering the damage from insect, deer browsing, frost, and nursery root disease (Oak 1992).

After oak seedlings and sprouts are established on a site, light and competition from shade-tolerant species become potential limiting factors to adequate development. Light is important for seedling survival, height, biomass growth and compositional change (Barnes et al. 1980, Dey 2002). A minimum light level is required by oak seedlings to produce enough carbohydrate to survive and grow. Full light is necessary for seedlings to develop into mature trees. However, for oaks, light intensity near the floor of hardwood stands is usually equal or lower than the compensation point, which is the light intensity at which the amount of carbon gains from photosynthesis equals the amount that loses from respiration (Barnes et al. 1980, Hodges and Gardiner 1993). Under a dense canopy, initial survival and growth of oak seedlings primarily depends on cotyledon reserves. Once the reserves are depleted, photosynthesis will be necessary. Under heavily shaded growing conditions (< 5% full sunlight), oak seedlings will have only one flush of shoot growth (Lockhart et al. 2003). In low light beneath mature stands, the inability to keep a positive carbon balance is the main reason for the lack of oak advanced regeneration (Lorimer 1993). Oak is less shade-tolerant compared to its competitors (Dey 2002), and sufficient light is important for oaks to compete effectively with other hardwoods. Insufficient light will restrict oak regeneration and recruitment into the overstory (Lorimer 1993, Johnson et al. 2002, Jensen and Karbrick 2007).

Oak species vary in response to light and competition in terms of shade tolerance and diameter growth rate (Johnson 1965). White oak is a comparatively slow-growing species. The Forest Resources Evaluation data in Central States indicate that the 10-year dbh average growth for white oak was 3.0 cm (1.2 in) for seedlings and saplings, 3.5 cm (1.37 in) for poles, and 4.7 cm (1.84 in) for sawtimber. These rates were slower than black oak *(Q. velutina*) and scarlet oak, but faster than hickory and beech. Scarlet oak grows fast in diameter among associated oaks especially on poor sites (Campbell 1965). Post oak (*Q. stellata*) grows slowly in height and is easily overtopped by other trees. White oak species are more shade-tolerant than red oak species (McGee 1981) and are generally classified as intermediate in shade tolerance. They are often the dominant species in certain stands because of their ability to tolerate shade under a forest canopy for a long time and to respond well after release. Black oak is also intermediate in shade tolerance. It is less shade-tolerant than its associates, and if seedlings attempt to establish under fully-stocked overstories, the seedlings usually die within a few years. Scarlet oak is classified as very intolerant of shade. This intolerance explains why it is usually present as a dominant or codominant on dry sites but absent in the suppressed position and also why thinning can greatly increase the growth and quality of scarlet oak (Dwyer et al. 1987). Post oak is classified as intolerant of shade and is often in the codominant position in the overstory.

Cutting has profound effects on microclimatic factors, such as air temperature, soil temperature, humidity, light, wind speed, precipitation, and solar radiation. These factors have been proven to be critical in forest ecological processes with a direct or indirect influence on seed germination, plant photosynthesis, respiration, growth, mortality and litter decomposition (Zheng et al. 2000, Iverson et al. 2004). As canopy is removed, the range of ground temperature increases and moisture regimes are changed. These changes will further affect tree regeneration, species composition and structure (Buckley et al.1998) since oaks are sensitive to soil moisture stress.

Overstory trees play a two-fold role in oak regeneration and survival. They provide necessary seeds for regeneration, but they also reduce light and compete for resources with young oaks. Reducing overstory density is an easy, cheap and commonly recommended method to encourage oak regeneration by increasing light in the understory (Loftis 1990b, Johnson 1993, Larsen et al. 1997). Open and larger crowns may also produce more acorns than closed crowns (Johnson 1994). After harvesting, the overall amount of light reaching the forest floor is also related to the opening size, aspect, slope, and position. Within an opening the northern portion receives the highest intensity of light, followed by center, western, eastern, and southern. In any opening size, light intensity decreases in the following order: south slopes, coves, and north slopes (Minckler et al. 1973). Successful establishment of advanced oak regeneration varies with slope position and aspect that control the light, heat, and soil moisture (Sander et al. 1984). According to Sander (1977), oak growth favors moister well-drained soils in coves and middle and lower slopes.

Intensity and pattern of forest harvesting or cutting affect species competition, which influences the subsequent forest composition and the rate of succession. In uncut plots, low light and soil moisture produce high stress, but uncut plots also exhibit low disturbance with slight deer browsing and less frost damage; in clearcut plots, high light and soil moisture produce low stress, but the harvest results in high disturbance with more deer browsing and more frost damage (Jonson et al. 2002, oak 1992). McGee (1975, 1986) studied seedling vulnerability to frost and how cold temperatures retarded development of early budbreak, indicating that these factors are reasons for the slow growth of released seedlings. Canopy openings allow sufficient sunlight to reach the forest floor which is important to oak regeneration, but at the same time, may promote the regeneration of competing species. Clearcuts which produce large openings with diameters at least twice that of the stand height may favor some invasive species that regenerate well when mineral soil is exposed. Partial cuts such as group selection and thinning create small gaps and may favor seed dispersal and species of intermediately shade-tolerance.

Oak regeneration and growth respond differently to the removal of overstory, depending on tree size and physiological condition (Larsen et al. 1997, Jensen and Karbrick 2007). Moreover, the density of reproduction in life stages such as seedling and sapling, has different distribution patterns across environmental gradients (Collins and Carson 2004). In a study of Tennessee forests, small oak seedlings were most abundant on productive soils and mesic landform position, whereas large oak seedlings favored less productive soils and drier landform position (Chadwell and Buckley, 2003). Landforms are important to tree growth because they affect local water distribution and development of soil (Shifley and Brookshire 2000).

Considering the enormous value of oak forests, improving oak management is exigent to researchers and forest managers. Disturbance is important to successfully regenerate these species. The MOFEP was initiated in 1989 to examine vegetation dynamics including oak regeneration under a set of predetermined timber management scenarios. Even-aged (including clearcutting, intermediate cutting), uneven-aged (including single-tree and group selection) and no harvest management (the control) were conducted in the oak forest ecosystem of the Missouri Ozarks (Brookshire and Shifley 1997, Brookshire and Dey 2000). The main objective of this study was to examine the effects of five harvesting methods on the composition and size structure of oak seedlings and saplings on treated sites using the1990-2006 MOFEP monitoring data.

## Methodology

### Study Area

The MOFEP includes nine sites ranging in size from 309 to 508 hectares, located in Carter, Reynolds, and Shannon Counties in the southeast Missouri Ozarks (Figure 2.1). Before harvesting, trees in study areas were mostly free from manipulation for at least 40 years (less than 5 percent of area disturbed). The study area is mostly within the Current River Oak Forest Breaks and the Current River oak-pine woodland hills landtype associations of the Ozark Highlands (Kabrick et al. 2000). Mean annual precipitation in the study area is 1.14 m, and most of the rainfall occurs in spring and fall.  Mean annual temperature is 13 ºC. The range of mean daily temperature is from -0.5 ºC in January to 24.8 ºC in August. The elevation ranges from 171 to 360 m and slope from 0 to 60 percent. The dominant soil parent materials include hillslope sediments, loess, and residuum (Meinert et al.1997, Kabrick et al. 2000).

### Study Design and Harvest Management

The nine MOFEP sites (compartments) are grouped geographically into three replicated blocks. Each block contains one even-aged, one uneven-aged and one no-harvest site. Even-aged management (EAM) includes harvesting by clearcutting and intermediate cutting (conducted in sites 3, 5, and 9). Uneven-aged management (UAM) includes harvesting with single-tree selection and group selection (conducted in sites 2, 4, and 7). No-harvest management was the control in the experiment (conducted in sites 1, 6, and 8). The first-entry harvests were initiated May-November of 1996 after the pre-harvesting inventory was performed in 1990 and 1995. On the EAM sites, 129 hectares were clearcut (11 %) and 166 hectares (15 %) were thinned. On the UAM sites, 860 hectares (57 %) were treated with single-tree and group selection (Kabrick et al. 2000). The detail of the study design was described by Brookshire and Shifley (1997), Shifley and Brookshire (2000), and Jensen and Kabrick (2007).

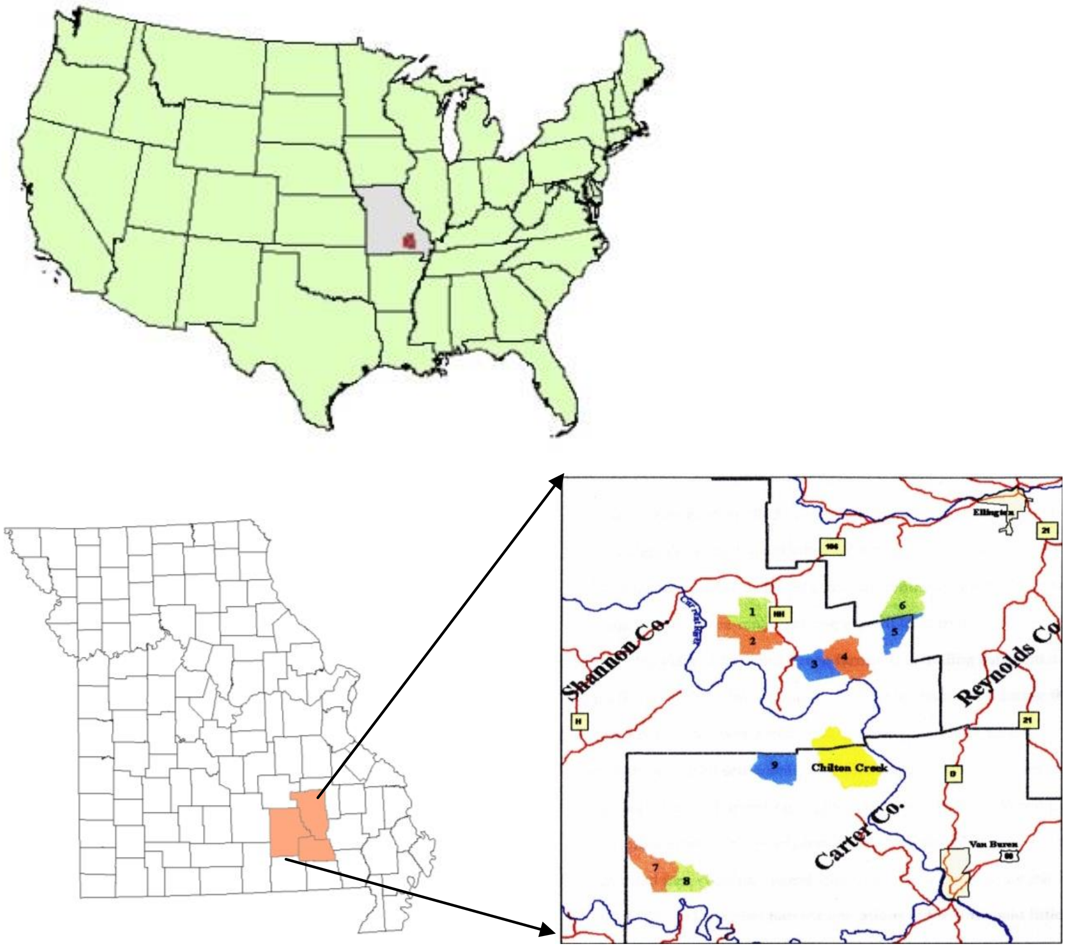


Figure 2.1 Location of nine MOFEP experimental sites (No harvest -sites 1, 6 and 8, uneven-aged management- sites 2, 4 and 7, and even-aged management - sites 3, 5 and 9).

The even-aged management was implemented according to MDC Forest Land Management Guidelines set up in 1986 and followed Roach and Gingrich (1968). The selected plots usually have mature or over-mature trees, poles, or small sawtimber that will yield enough commercial benefit without reducing residual growing stocking below B-level (Gingrich 1967). Rotation lengths for each site are 80-100 years. This results in a regulated harvest of 10-12 percent of the area per entry on a 10-year re-entry schedule. The principal means of stand regeneration was using clearcutting with reserves. Ten percent of each treated site was left as “old growth" and excluded from harvest in perpetuity. The desirable tree size class distribution on the remaining area is 10 percent seedlings, 20 percent small trees(6-14cm dbh), 30 percent poles(14-29cm dbh) and 40 percent sawtimber (>29cm dbh) (Brookshire et al. 1997). These reserve trees may provide food and habitat for wildlife.

The uneven-aged management also follows the MDC Forest Land Management Guidelines (1986). Harvest prescriptions follow Law and Lorimer (1989). Ten percent of each site was initially reserved as "old growth" and the remaining 90 percent was treated with uneven-aged management. For single-tree and group selection, rotation and re-entries coincide with those of even-aged management. Group selection harvests create openings with diameters which are equal to 1-2 times the height of overstory trees (Smith 1986) depending on location, aspect, and the forest manager's general design to improve stand quality. At MOFEP, each uneven-aged management site was divided into management units which were less than 10 hectares each, and the management objectives were set for largest diameter tree (LDT), residual basal area (RBA), and q-level. The target RBA which equaled B-level stocking was chosen. The target LDT was around 46 cm and 66 cm dbh for low site quality and high site quality, respectively. The q-value ranged from 1.3 to 1.7.

The no-harvest management was used as the experimental control at MOFEP. Wildfire and large-scale insect outbreaks will be suppressed in those sites. Natural disturbances occurred as on any other forest lands.

**Data Collection**

Since the initial inventory in 1990, woody vegetation has been re-inventoried every three to five years (1995, 1998, 2002, and 2006) across the nine study sites. A total of 648 permanent inventory plots (0.2 ha each) were established for sampling vegetation on the nine MOFEP sites with 70 to 76 plots per site (Shifley and Brookshire 2000). On the 0.2-ha circular plot (Figure 2.2), woody vegetation ≥ 11.4 cm (4.5 in) diameter at breast height (dbh) was measured. Woody vegetation (3.8 cm ≤ dbh < 11.4 cm) (1.5 ~ 4.5 in) was measured on the four 0.02-ha subplots located within the 0.2-ha main plot. Woody vegetation (< 3.8 cm dbh, ≥ 1m tall) was measured on four 0.004-ha subplots nested within each 0.02-ha subplot. Tree species, density, dbh, crown class (dominant, co-dominant, intermediate, and suppressed), and status (live, dead, blown-down, den, and cut) were sampled in each subplot/plot. Physical characteristics such as slope, and aspect of each plot were also collected.

**Data Analysis**

Ecological land types (ELTs) are defined by characteristics of geologic formation, slope, aspect, soil depth to bedrock and indicator plant species (Shifley and Brookshire 2000). Considering the potential variation of oak reproduction by site condition, in this study, the ELTs were classified into to dry sites (321 plots) and mesic sites (315 plots). Dry sites are land types with aspect range from 315 to135º, south- and southwest-facing backslopes; mesic sites are land types with aspect range from 135 to 315º, north- and northeast-facing slopes (Kabrick et al. 2008).

As shown in Figure 2.3, reproduction population of oaks was grouped into three size classes: size 1 (ht > 1m, dbh < 1.3 cm), size 2 (1.3 cm ≤ dbh < 3.8 cm), and size 3 (3.8 cm ≤ dbh < 11.4 cm) to capture the dynamics of oak seedlings and saplings under various treatments. The size 1 class was composed of seedlings from three sources: acorns, stump sprouts and seedling sprouts. The timber harvesting treatments and subsequent change of abiotic and biotic factors affect seedling (size 1) recruitment and the transition (growth and mortality) between sizes 1 and 2, sizes 2 and 3, and size 3 and overstory trees which can be measured by stem density and relative proportion (Rogers and Johnson 1998, Woodall et al. 2008). A total of 321 plots were included on dry sites and 315 plots on mesic sites. In each group, plots were further reorganized into one of the 15 combinations of 5 harvesting methods by 3 replications (sites) for statistical analysis. In this study, white oak, black oak, scarlet oak, and post oak are the four dominant species with 71 percent basal area of the mature forests (Kabrick et al. 2004). Reproduction stem density and proportion of these four oaks and all other non-oak species in combination at 1995 (pre-harvest), 1998, 2002 and 2006 (post harvest) were analyzed statistically. The original data indicated less than three percent reproduction developed from stump sprouts; so in this study, they were combined with other sources of regeneration.

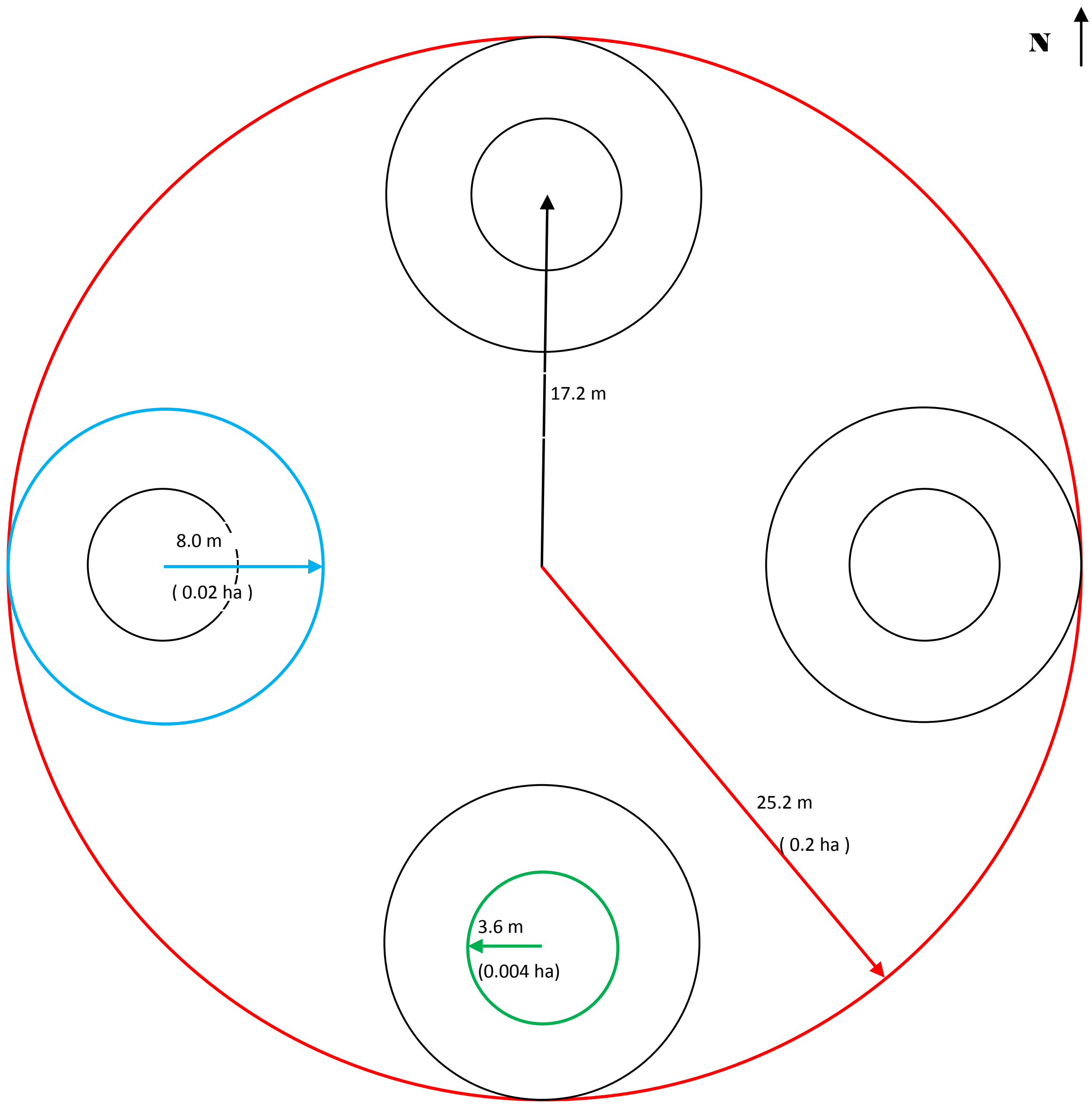


Figure 2.2 Diagram of the permanent cluster plot layout used on the forest vegetation study of the Missouri Ozark Forest Ecosystem Project

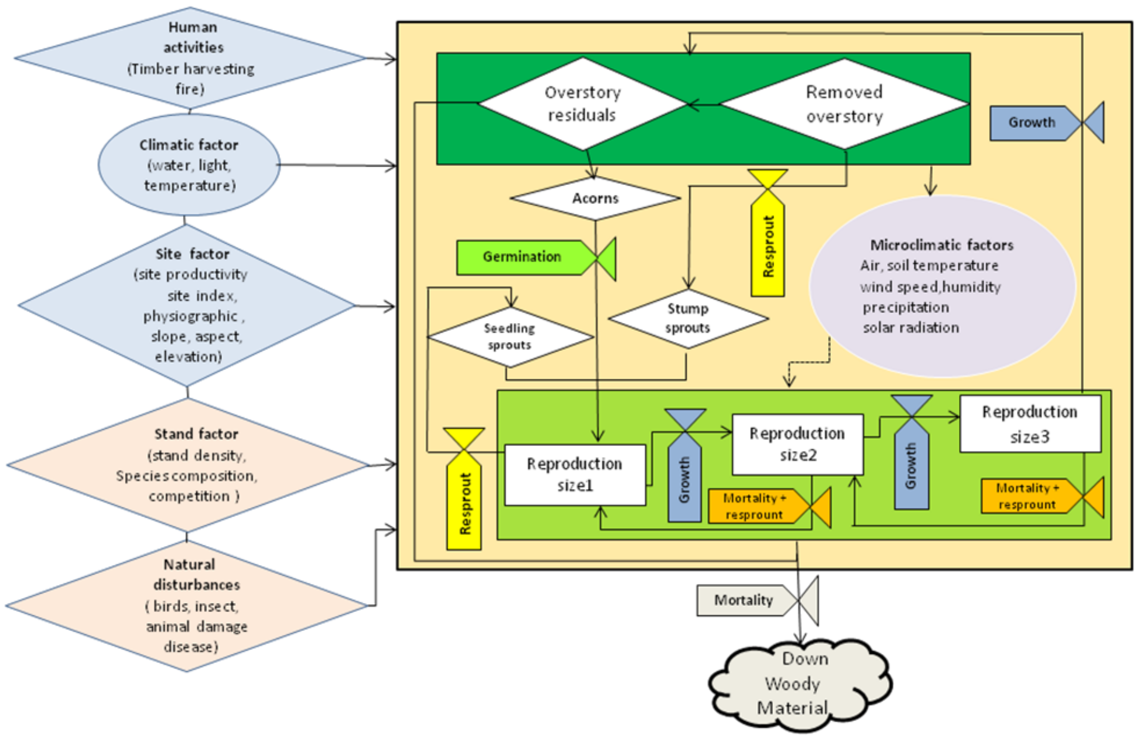


Figure 2.3 The conceptual model of the dynamics of oak forests following overstory management

Data for the treatment effects were evaluated using the GLM procedure (SAS version 9.2, SAS institute, Cary, NC). ANOVA (analysis of variance) and MANOVA (multivariate analysis of variance) were used to analyze treatment effects (Gotelli and Ellison 2004). Significance was accepted at the $P \leq 0.05$ level for all the tests. One-way ANOVA was used to test, for a given oak species, whether the means for five treatment groups were taken from the same sampling distribution. For one-way ANOVA, the model is

$$Y_{ij} = \mu + A_i + \varepsilon_{ij} \tag{2-1}$$

where $Y_{ij}$ is the replicate $j$ associated with treatment level $i$. In this study, it represents the density of oak reproduction. $\mu$ is the true grand mean. $A_i$ represents the additive linear component associate with each level $i$ of the treatment $A$. The error $\varepsilon_{ij}$ is assumed to be normally, independently and identically distributed, with mean zero and variance $\sigma^2$. Fisher's LSD (Least Significant Difference) was used to determine the significant differences between group means in the analysis of variance setting. One-way MANOVA was used to test whether the three vector means (reproduction size 1, 2 and 3) for five treatment groups are sampled from the same sampling distribution. The model is

$$Y = \mu + A_k + e_{kl} \tag{2-2}$$

where $Y$ is the matrix of measurements, $\mu$ is the grand mean, $A_k$ is the matrix of deviations of the $k^{th}$ treatment from the sample grand mean, and $e_{kl}$ is assumed to come from a multivariate normal distribution, and all groups have common homogeneous variance-covariance matrices. Four test-statistics are generated, Wilk's lambda, Pillai's trace, Hotelling-Lawley's trace, and Roy's greatest root. All four of these tests appear to be nearly equivalent for the extremely large sample sizes. For moderate sample size, when they differ, Pillai's trace is often used because it is robust. Both ANOVA and MANOVA were applied in statistical tests of post-harvest inventory years 2002 and 2006. Year 1998 was skipped since it was too close to the harvesting year 1996.

## Results

This section described the effects of timber harvesting treatments on oak regeneration in terms of proportion of oak reproduction as a whole, ratio of white oak group to red oak group, proportion of four major oak species and three size classes.

### Proportion of oak reproduction as a whole

On dry sites, results showed marginally significant difference (*P* = 0.08) in the proportion of oak reproduction among the five harvesting methods by year 6 (Figure 2.4a). However, by year 10, clearcutting significantly (*P* = 0.02) increased the proportion most of all the harvesting methods which suggested oak composition had been improved most significantly. On mesic sites, there was no significant difference (*P* = 0.4) among the five harvesting methods by year 6 or year

10 (Figure 2.4b). On dry sites, the mean proportion in year 6 and year 10 was 0.33 which was higher than of the proportion of 0.21 on mesic sites.

**Ratio of white oak group to red oak group**

In this study, only the four major oak species were included in analyses. White oak and post oak were grouped as the white oak group, and black oak and scarlet oak were included in the red oak group. The ratio represents the ratio of reproduction density of the white oak group to that of the red oak group. The results indicated there were no significant differences of ratios across treatments in year 6 or year 10 on any land type (Figure 2.5). On dry sites, the mean ratio of year 6 and year 10 was 1.67 which was lower than that on mesic sites of 3.42.

**Reproduction of white oak, black oak, scarlet oak and post oak**

Means of reproduction density of all regeneration sizes (trees per hectare (TPH)) and the corresponding proportion of the reproduction of four oak species in each predetermined treatment unit were summarized (Table 2.1). Proportion was calculated as the ratio of the density of the given oak species to the density of all oak and non-oak species. Proportion differences were compared before (1995) and after harvesting (inventory years 2002 and 2006). Analysis of pre-harvest density indicated that on all sites, especially mesic sites, white oak had the predominant position compared to the other three oak species.

Table 2.1 Reproduction density (TPH) and composition proportion (% in brackets) of oak and non-oak species before harvesting (year1995).

| | White oak | Black oak | Scarlet oak | Post oak | Other Species |
|---|---|---|---|---|---|
| **DRY SITES** | | | | | |
| Nocut | 1006(11.2) | 524(5.8) | 375(4.2) | 197(2.2) | 6906(76.7) |
| Intermediate cut | 654(7.4) | 85(1.0) | 97(1.1) | 32(0.4) | 8021(90.2) |
| Single-tree selection | 1083(11.8) | 353(3.9) | 209(2.3) | 172(1.9) | 7329(80.1) |
| Group selection | 1008(12.3) | 302(3.7) | 259(3.2) | 366(4.5) | 6249(76.4) |
| Clearcut | 1333(15.8) | 846(10.0) | 633(7.5) | 75(0.9) | 5529(65.7) |
| **MESIC SITES** | | | | | |
| Nocut | 796(6.1) | 123(0.9) | 110(0.8) | 136(1.1) | 11802(91.0) |
| Intermediate cut | 902(6.8) | 100(0.8) | 187(1.4) | 52(0.4) | 12057(90.7) |
| Single-tree selection | 1000(8.7) | 157(1.4) | 168(1.5) | 108(0.9) | 10024(87.5) |
| Group selection | 976(11.4) | 317(3.7) | 121(1.4) | 33(0.4) | 7091(83.1) |
| Clearcut | 580(5.3) | 186(1.7) | 167(1.5) | 17(0.2) | 10028(91.3) |

Harvesting resulted in a shift among the reproduction of mixed-oak forest stands (Figure 2.6). In this study, for a given species, the proportion was calculated as the ratio of the reproduction density of a given species to the reproduction density of all oak and non-oak species in a treatment. Compositional shifts can be indicated by the proportion difference between post-harvest (an inventory year of interested) and pre-harvest (year 1995).

Under either site condition, non-oaks, the competitor of oaks, had a greater increase in both density and proportion after harvesting. This increase is proportional to the overstory gap. Our research suggested that though the clearcutting treatment significantly increased the density of oaks (Figure 2.4), it did not increase compositional proportion of each of the species. On dry sites, by year 10, group selection, clearcutting and single-tree selection decreased the proportion of white oak with 6%, 4% and 3%, respectively (Figure 2.6a). For black oak, by year 10, there was an increased proportion in the intermediate cutting and clearcutting with 2% and 3%, respectively. The harvest methods did not influence the proportion of scarlet oak reproduction except for a 5% decrease in the clearcut areas by year 10. On mesic sites (Figure 2.6b), overall, the range of proportional change was less than that on dry sites. There was a shift from non-oak to oak in clearcut areas. In single-tree selection, that result was reversed.

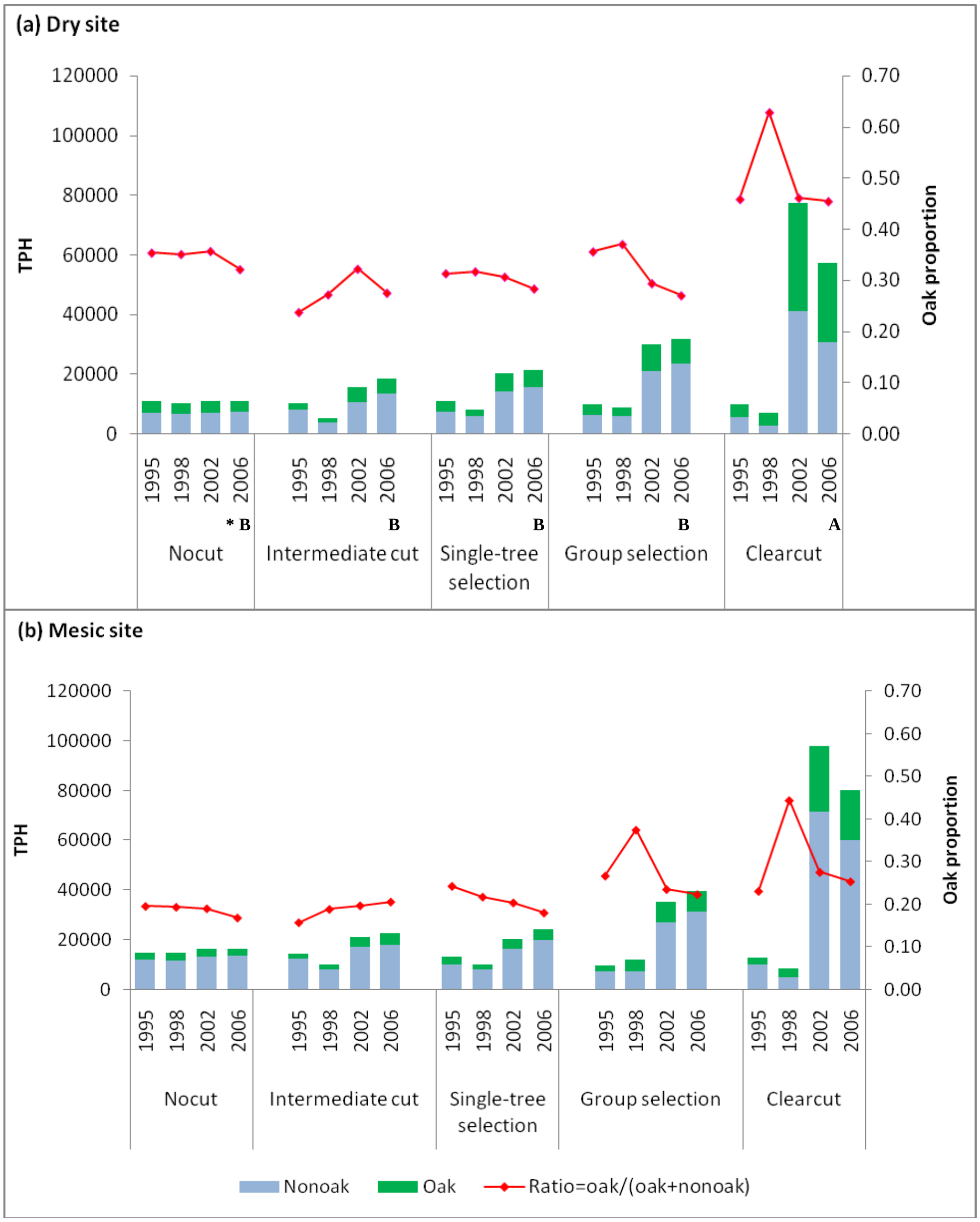


Figure 2.4 Density of oak and non-oak reproduction (ht>1m tall, <11.4 cm DBH) and ratio of oak to non-oak regeneration by inventory year, regeneration methods and ELT.

Note: * In year 2006, same uppercase letters represent the means of ratio are not significantly different under different harvesting methods. The absence of letters in years 2002 or 2006 represents no significant difference of the means of ratio under different harvesting methods in that year.

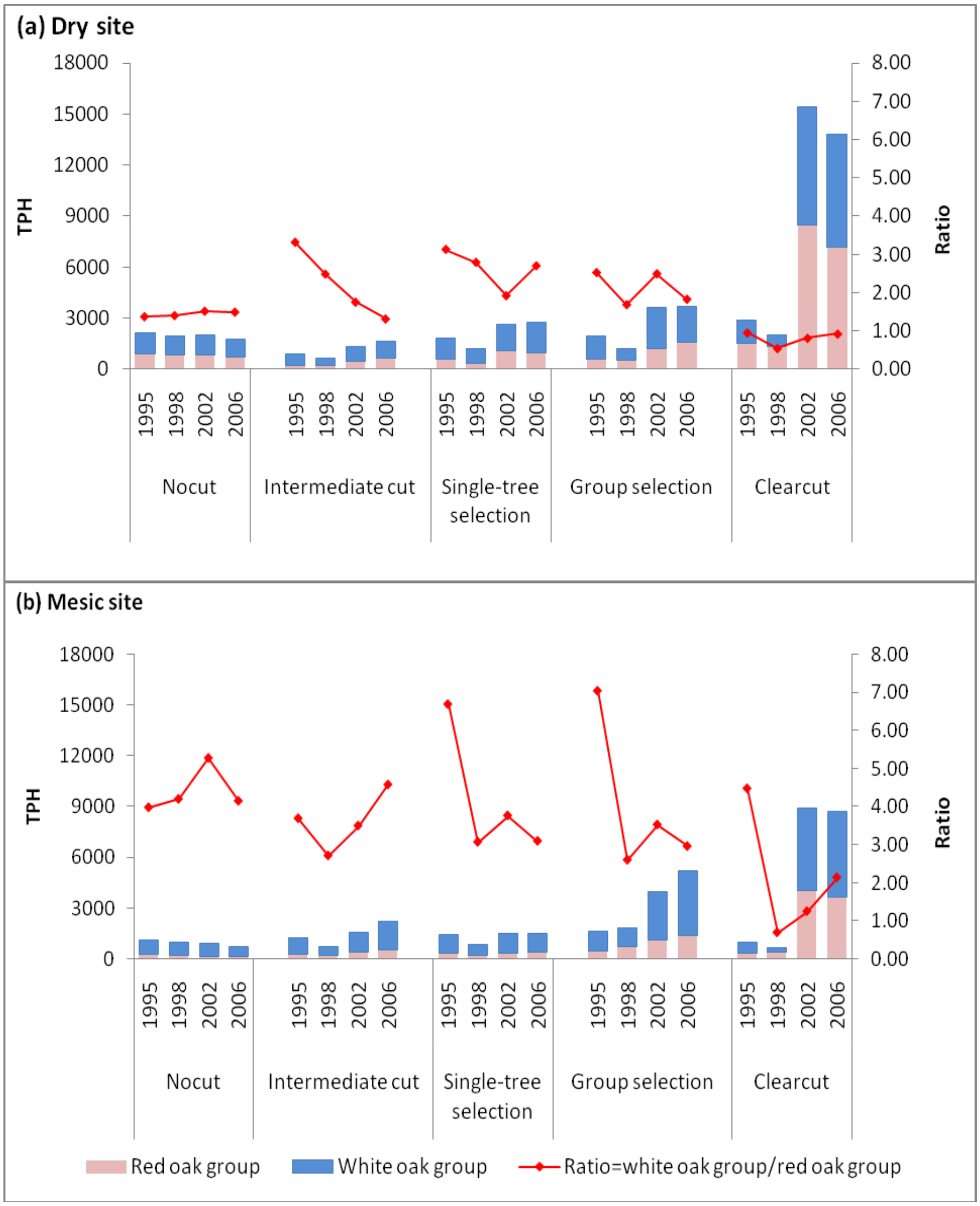


Figure 2.5 Density of white oak group and red oak group reproduction (ht>1m tall, <11.4 cm DBH) and ratio of white oak group to red oak group by inventory year, regeneration methods and ELT

Note: The absence of letters in years 2002 or 2006 represents no significant difference of the means of ratio under different harvesting methods in that year.

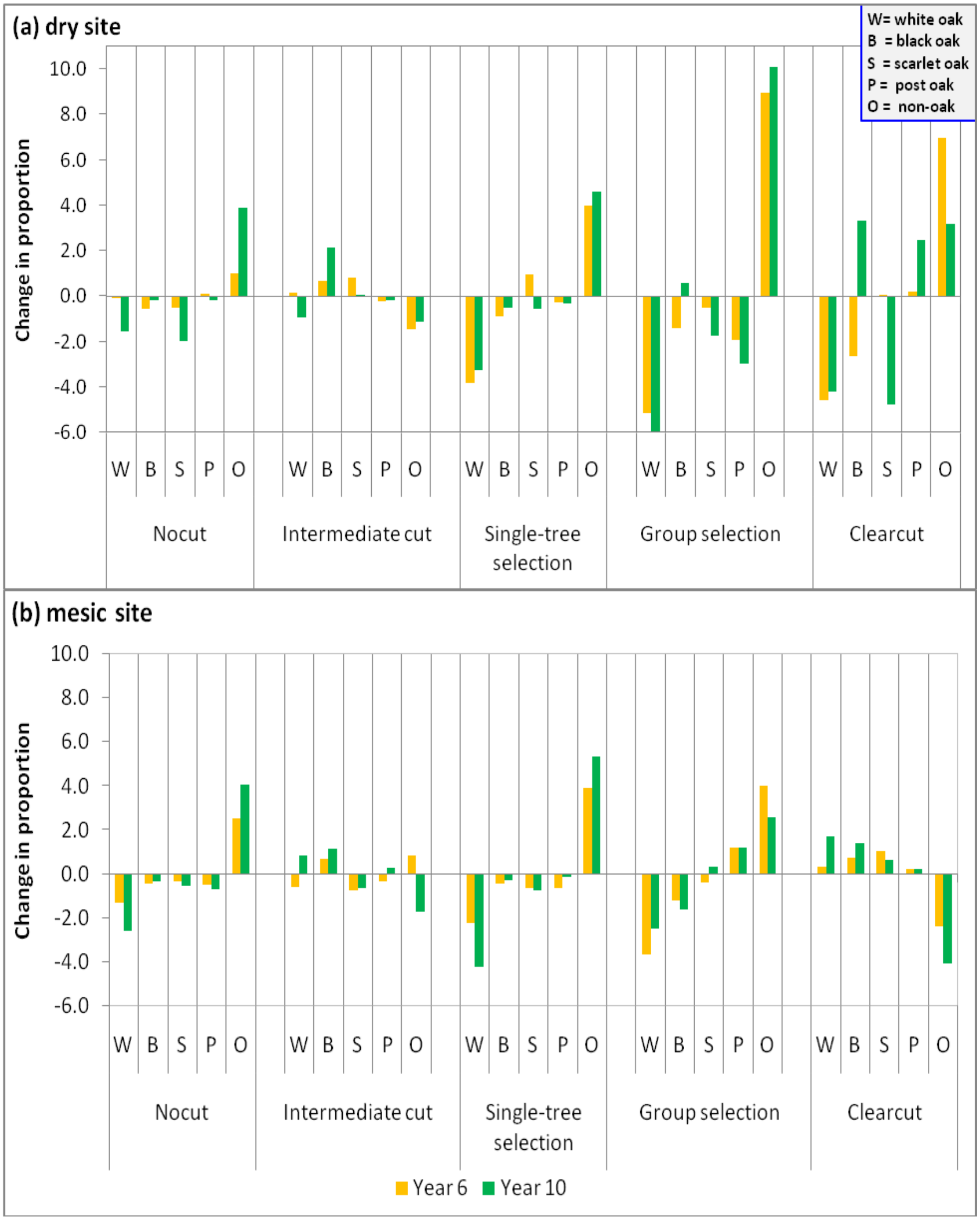


Figure 2.6 Change in compositional proportion change of white oak, black oak, scarlet oak, post oak and non-oak reproduction under treatments by year 6 and 10

**Size structure of oak reproduction**

*Density of total reproduction*: For both white oak and black oak, clearcutting increased total reproduction density (sum of all sizes) most significantly by both year 6 and year 10 on either dry or mesic sites (Figures 2.7 and 2.8). The density of white oak and black oak reproduction was increased most significantly by clearcutting followed by group selection in year 6 and 10 on either dry site or mesic sites.

*Size structure:* MANOVA revealed that there was a significant difference ( *Pillai's trace,* overall multivariate test, $P$ = 0.0141) in density of white oak among the three sizes under the five harvesting methods by year 10, but only on mesic sites. For other species, there was no such difference in year 2002 or 2006 on dry or mesic sites. For a given reproduction size of white oak, black oak and scarlet oak, ANOVA indicated there were significant differences across the five harvesting methods. Differences between least square means were determined using Fisher's least significant difference (LSD) (Table 2.2). For white oak and black oak, clearcutting improved the smaller size (size 1 or 2) more significantly than other methods (Figures 2.7 and 2.8). By year 10, this larger size (size 3) responded well in clearcutting. For scarlet oak, the significant treatment difference only existed by year 6.

Compared to the no harvest treatment, intermediate cutting, single-tree selection and group selection increased the proportion of size 1 seedlings of black and scarlet oak on all sites (Figures 2.7, 2.8 ). This was true also for white oak on mesic sites using either group selection or clearcutting. Even though seedling and sampling density increased dramatically following the clearcutting, competition-caused mortality was intense.

Table 2.2 Fisher's least significant difference (LSD) comparison of oak reproduction densities across treatments for three oak regeneration sizes

| | Dry site | | | | | | Mesic site | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2002 | | | 2006 | | | 2002 | | | 2006 | | |
| **white oak** | **size 1** | **size 2** | **size 3** | **size 1** | **size 2** | **size 3** | **size 1** | **size 2** | **size 3** | **size 1** | **size 2** | **size 3** |
| **P_value** | 0.041 | <0.0001 | 0.631 | 0.117 | <0.0001 | 2E-04 | 0.015 | <0.0001 | 0.958 | 0.01 | 4E-04 | 2E-04 |
| Nocut | b | b | | | b | b | c | c | | c | b | c |
| Intermediate cut | b | b | | | b | b | bc | c | | bc | b | c |
| Single-tree selection | b | b | | | b | b | bc | c | | c | b | c |
| Group selection | ab | b | | | b | b | ab | b | | ab | a | b |
| Clearcut | a | a | | | a | a | a | a | | a | a | a |
| **black oak** | **size 1** | **size 2** | **size 3** | **size 1** | **size 2** | **size 3** | **size 1** | **size 2** | **size 3** | **size 1** | **size 2** | **size 3** |
| **P_value** | 0.0002 | <0.0001 | 0.303 | 0.010 | 0.0004 | <0.0001 | 0.0359 | 0.007 | 0.001 | 0.097 | 0.0002 | 0.009 |
| Nocut | b | b | | b | b | b | b | b | b | | b | b |
| Intermediate cut | b | b | | b | b | b | b | b | b | | b | b |
| Single-tree selection | b | b | | b | b | b | b | b | b | | b | b |
| Group selection | b | b | | b | b | b | ab | b | b | | b | b |
| Clearcut | a | a | | a | a | a | a | a | a | | a | a |
| **scarlet oak** | **size 1** | **size 2** | **size 3** | **size 1** | **size 2** | **size 3** | **size 1** | **size 2** | **size 3** | **size 1** | **size 2** | **size 3** |
| **P_value** | 0.048 | <0.0001 | <0.0001 | 0.849 | 0.337 | 0.285 | 0.006 | <0.0001 | 3E-04 | 0.547 | 0.308 | 0.094 |
| Nocut | b | b | b | | | | b | b | b | | | |
| Intermediate cut | b | b | b | | | | b | b | b | | | |
| Single-tree selection | b | b | b | | | | b | b | b | | | |
| Group selection | b | b | b | | | | b | b | b | | | |
| Clearcut | a | a | a | | | | a | a | a | | | |

Note: The blank cell and the absence of post oak denote no significant difference of size density across treatments.

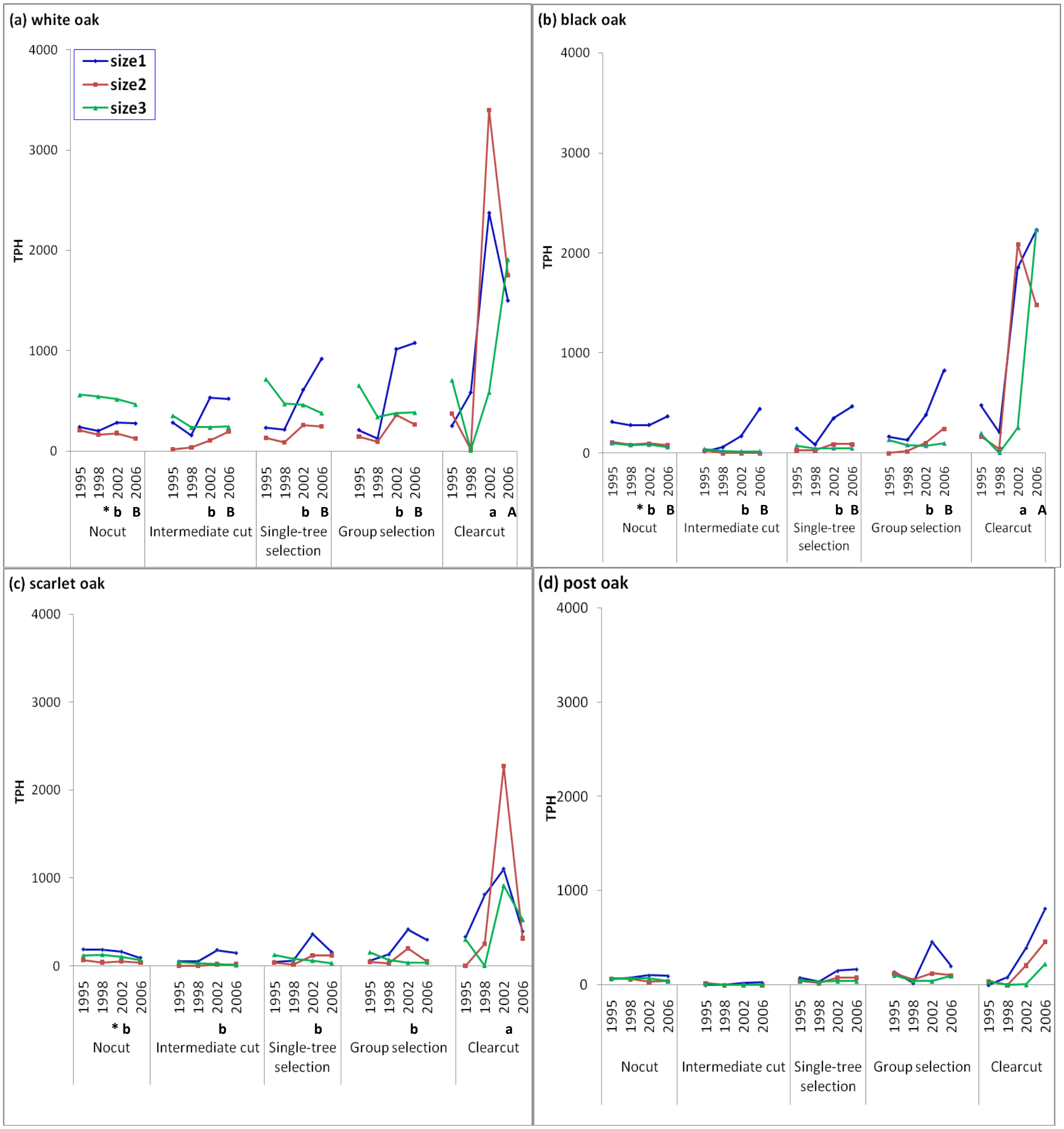


Figure 2.7 Density of oak reproduction by inventory year and regeneration methods on dry sites at MOFEP

Note: * Same lowercase letters represent means of total reproduction (sum of all sizes) density of a given species are not significantly different in 2002. Same uppercase letters represent that of year 2006. The absence of letters represents no significant difference in 2002 or 2006.

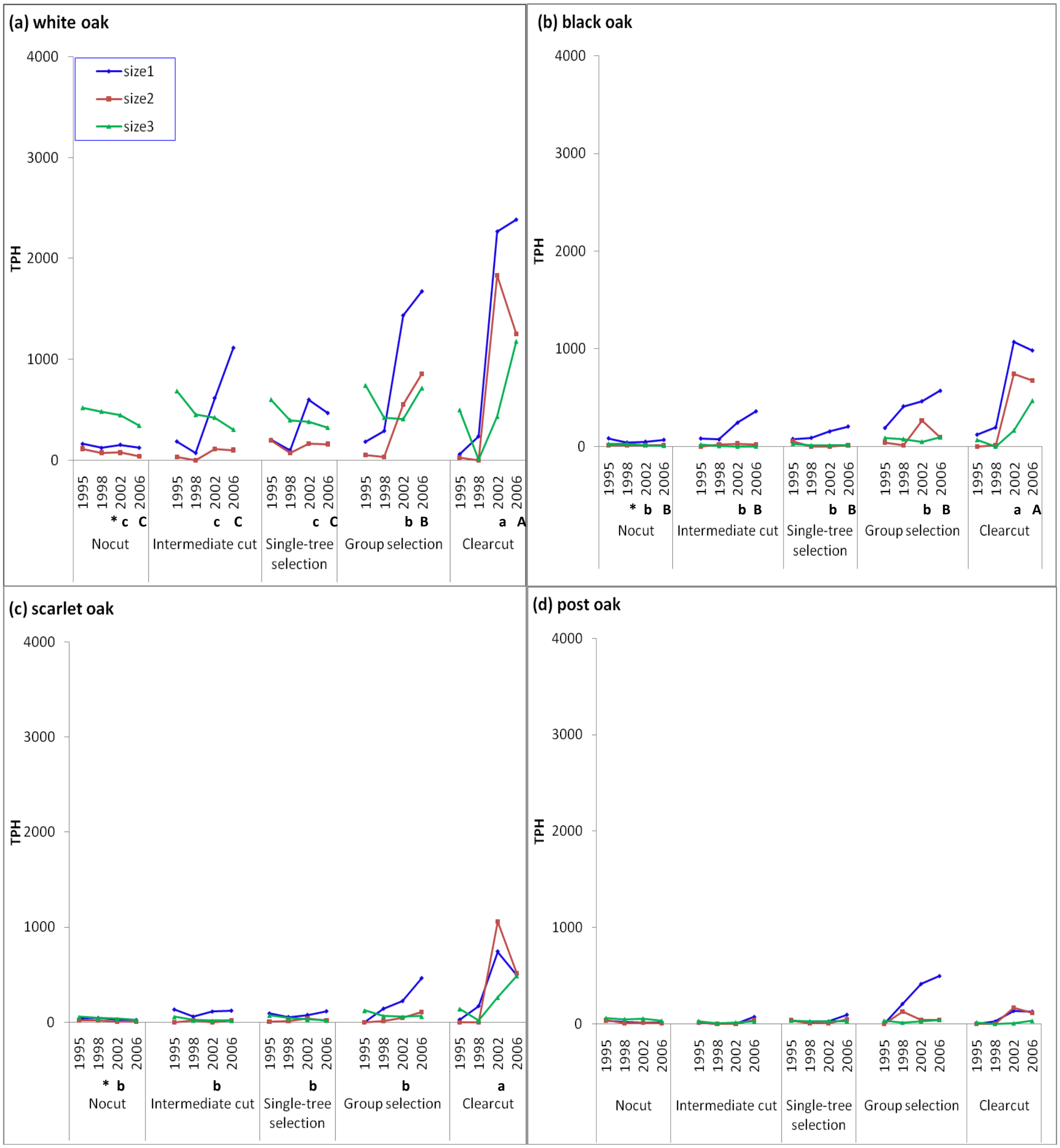


Figure 2.8 Density of oak reproduction by inventory year and regeneration methods on mesic sites at MOFEP.

Note: * Same lowercase letters represent means of total reproduction (sum of all sizes) density of a given species are not significantly different in year 2002. Same uppercase letters represent that of year 2006. The absence of letters represents no significant difference in year 2002 or 2006.

# Discussion

## Change of species composition of oak reproduction

*Composition of oak reproduction as a whole:* The greater the intensity of harvesting, the greater the increase of oak reproduction. However, compared to associated competitors, oaks are less shade-tolerant and they grow at rates slower or equal to competitors. More oaks were observed on dry sites than mesic sites. This result is consistent with a previous study that indicated that oaks are more abundant in low-quality site (Hicks 1998). On poorer-quality sites, oak are subjected to less competition, and contain adequate advance reproduction. Before harvesting, abundant reproduction population with larger size is essential to the success of regeneration (Johnson et al. 2002). However, on good sites, fast-growing competition may soon overtop the oak seedling (Crow 1988). Most oaks have a conservative growth strategy, and young seedlings first develop a root system using photosynthetic resources. Upon germinating, oak send a strong radicle deep into soil that enables oaks to establish a taproot and develop a high root: shoot ratio. Such growth strategy gives oaks a morphological adaption to succeed on dry-mesic or xeric sites where moisture may be limiting (Dickson 1991). Once the seedlings are released, if they do not have strong root system or adequate shoot height, shoot growth will be slow until the root system develops and competition from other competitors such as red maple can be curbed (Sander 1972, Hodges and Gardiner 1993).

*Ratio of white oak group to red oak group:* In a comparison of the pattern of the ratio of white oak to red oak on dry and mesic sites, intermediate cutting and single-tree selection induced a reverse result (Figures 2.5 a, b), which can be explained by the different response to ELT by white oak group and red oak group reproduction. Kabrick et al. (2008) indicated the regeneration of the red oak group has significant relationship with ELT, but for the white oak group, there was no relationship. Red oak species grow faster than white oak on dry sites, and white oaks are more shade-tolerant than red oaks (Hicks 1998). This may explain why white oak species are more abundant on wet sites than red oak species, and the average ratio of white oaks to red oaks on dry sites was lower than that on mesic site (Figure 2.5). On mesic sites, two even-aged harvesting methods produced a very similar pattern of ratio change; the two uneven-aged harvesting methods also produced a similar ratio pattern.

*Composition of reproduction of white oak, black oak, scarlet oak and post oak:* On average, harvesting decreased the compositional proportion of white oak reproduction. The removal of overstory benefits the shade-intolerant competitors of white oak, and the seedlings and saplings of white oak grow slower than many of their competitors in a mixed even-age stands with yellow-poplar, black cherry, northern red oak, scarlet oak, and eastern white pine (Hicks 1998). However, white oak reproduction maintains its dominant position among the four major oaks because of its intermediate shade tolerance and longevity (Figures 2.7a, 2.8a). Hicks (1998) also reported that white oak can be found with almost all the species in the central hardwoods region due to its wide distribution and great site tolerance.

Black oak is less shade-tolerant compared to many of its associates including white oak, chestnut oak, hickories, beech and maples (McGee 1981). This may explain the increase of black oak proportion after harvesting using the intermediate cut and clearcut harvests (Figures 2.6 a, b). These two treatments resulted in a compositional proportion shift from white oak to black oak which was consistent with previous studies (Hicks 1998) that stated even-age management is best suited to regenerate shade-intolerant species. Scarlet oak is classed as the most shade-intolerant of the upland oaks and it grows faster than most other oaks and hickories (Hicks 1998). On dry sites, using clearcutting, the compositional proportion of scarlet oak increased dramatically in 2002, but in year 2006, it decreased abruptly which due to the competition-induced mortality (Figures 2.6 a, 2.7 c), but on mesic sites, the shift in pattern is different (Figures 2.6 b, 2.8c). The different between dry and mesic sites is also obvious for black oak under cleacutting. However, for white oak, there was no obvious difference in compositional shift. This result is supported by Kabrick et al. (2008) who stated that there was only a significant relationship between ELT and red oak reproduction density.

### Change of size structure of oak reproduction

Group selection resulted in more small size of oak species than larger size which was a stable structure of oak stands. Different sizes of oak reproduction respond differently under various harvesting methods (Larsen et al. 1997, Jensen and Karbrick 2007). Chadwell and Buckley (2003) indicated small oak seedlings are likely to survive with productive soils and on mesic sites; large oak seedlings are likely to survive with less-productive soils and on drier sites (Chadwell and Buckley, 2003). For a long-term perspective, we will need to examine the effects of clearcutting on oak stability.

White oak is the most shade-tolerant of the important oak species in the central hardwood region (Rogers 1990). It is more tolerant when it is young (Hicks 1998). Under the no-cut method, density of size 3 of white oak reproduction decreased with time, while for size 1, the density had an increasing trend (Figures 2.7a, 2.8a). In this study, clearcutting was much more effective than the uneven-aged selection system for black oak regeneration (Figures 2.7b, 2.8b) which is consistent with the report of Sander and Clark (1971). However, shade-tolerant species such as maples can make significant and steady height growth until they develop a multi-storied layer of vegetation under a closed canopy (Lorimer 1984). Even when released from overstory suppression, only large stems of black oak have the ability to compete successfully; the seedlings will likely be overtopped (Sander 1972). In clearcut areas, large seedlings always kept up an increasing trend, but for size 1 and 2, growth either slowed or decreased in year 2006 after an abrupt increase (Figures 2.7b, 2.8b). Sander (1977) indicated that to produce a new oak stand after harvesting, relatively large oak stems must be present before harvesting the old stand. Compared to white oak and black oak, scarlet oak responded much more obviously in clearcutting, but a sharp decrease of all sizes followed the abrupt increase (Figures 2.7c, 2.8c) which was caused by the competition-induced mortality. Post oak is a slow-growing oak, and it did not show significant difference of density among the harvesting methods (Figures 2.7d, 2.8d). Although post oak is not as valuable as white oak for timber production, it is still important for wildlife habitat. Overall, the change of density on mesic sites is less than that on dry sites which provides further evidence that oak is more abundant on poor quality sites (Starkey et al. 2004).

As discussed earlier, many influential factors affect the population dynamics of oak regeneration, including biotic and physical, environmental factors (Barnes et al. 1980). Harvesting disturbance is only one factor. Edge effects from group selection method may damage reproduction by felling of surrounding trees within groups and the wounds produced during that disturbance may cause pathogenic effects such as oak decline (Oak et al. 1996). Successful natural oak regeneration requires a sufficient number and size of advance regeneration to be present. The regeneration potential of a stand can be expressed by the number, size and spatial distribution of these classes of reproduction (Sander et al. 1984).

Clearcutting contributed the most to improve oak reproduction, this result is the same as that reported by Jensen and Kabrick (2007), but it may induce potential issues related to forest fragmentation, soil erosion and long-term decline which will disrupt habitat connectivity in forests (Johnson et al. 2002). Additional studies need to be conducted to explore the details of oak regeneration dynamics in the future.

## Summary

Most harvesting treatments with the removal of the overstory improved the abundance of oak reproduction in size 1 which is a sign of a stable structure in the reproduction population. All harvesting methods resulted in increases in regeneration under treatments in year 6. These increase trends were sustained in year 10 except in the clearcut treatment. Clearcutting is the only method that significantly increased the total reproduction (seedling/sapling) density. Clearcutting is also the only treatment that resulted in seedling development into the larger sizes which is most likely adequate to provide a significant oak component in future stands. However, considering issues of long-term growth and forest fragmentation, clearcutting may not be the best regeneration scheme. Group selection may have potential to develop oak into future stands, but more time is still needed to observe these areas. Black oak and scarlet oak show limited development into the larger-size classes across all treatments except for clearcutting. Based on changes in seedling density, white oak was favored the most by the harvest treatments, followed by scarlet oak and black oak. Even-aged management increased the compositional proportion of black oak reproduction. White oak grows slower than its competitors; and harvesting decreased its compositional proportion of all tree species on the study sites.

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# Chapter III

## EFFECTS OF TIMBER HARVESTING ON THE MORTALITY OF OVERSTORY OAK RESIDUALS IN UPLAND OAK FORESTS IN THE MISSOURI OZARKS

### Introduction

### Current condition of oak decline and mortality in the Missouri Ozarks

In the Missouri Ozarks, more than 40,000 ha of oak-dominated forests were affected by serious oak decline early in this decade (Lawrence et al. 2002). Wargo et al. (1983) described the main symptoms of oak decline: dieback of crown leave accompanied by chlorotic, dwarfed, sparse or brown foliage, and epicormic sprouts on stems or branches. Oak decline-induced mortality has reached an unprecedented level because red oaks (black oak, scarlet oak) are the most common species on poor quality sites in the Ozark Highlands (Starkey et al. 2004, Fan et al. 2008). Moreover, thousands of acres of forests containing red oaks are dense or overmature which increases the susceptibility to oak decline. Oak decline and mortality raise many economic, environmental and sociological concerns. Oak decline adversely affects oak regeneration and wildlife habitat as large losses of dominant oaks may greatly reduce acorns yield. Declining trees increase the risk of injury caused by falling limbs and boles, and that can reduce recreational activities such as hiking, camping, and hunting in the forests. Accumulating snags, dead branches, twigs and leave can lead to increased fire hazard.

### Hypothesis of oak decline and mortality

Oak decline is a slow-acting dieback process and eventually leads to morality of oak trees. It is also a process along with forest succession that spans a long temporal scale. Oak decline is a dynamic process which occurs with various ecological processes on a wide range of site scales (Wang et al. 2007, Spetich and He 2008). When the stresses are removed, trees may recover if not attacked by secondary agents or the damage is not fatal (Chadwell and Buckley 2003). A tree will die if the stress is sufficiently severe or prolonged. Aside from natural dying and recovery, human disturbances also play a role in forest dynamics. Harvesting reduces biomass to various extents and it changes the composition of regeneration sources (Millers et al. 1989).

There is no single factor that causes decline. Trees can be killed by a combination of damaging agents. Previous studies indicated that oak decline is caused by a complex interaction of ecological and environmental stresses including predisposing factors (advanced tree age, site quality, stand condition), inciting factors (drought, frost, ice, or wind), and contributing factors (oak borers and other insects, root diseases) which will cause further stress and damage to the trees (Law and Gott 1987, Starkey and Oak 1989, Lawrence et al. 2002, Fan et al. 2006).

***Predisposing factors****:* Relatively old (older than 70 years) or large trees (dbh> 14 inches) are most susceptible to decline. When site index equals tree age, the risk of oak decline increases, especially for red oaks (Oak et al. 1996, Clatterbuck and Kauffman 2006). Age is a risk factor to trees on the MOFEP sites. Before harvesting, most overstory trees ranged in age from 50 to 70 years old; trees older than 100 years occur in every site, and a few are over 140 years (Brookshire and Dey 2000 ). Sites that are located on ridgetops and south and west-facing slopes are most susceptible to oak decline. Shallow soil (< 18 inches) and rocky soils that have lower productivity are predisposing factors to oak decline especially for the red oak group (Starkey and oak 1989, Starkey et al. 2004, Clatterbuck and Kauffman 2006).

Besides site factors, stand density, tree species and crown class are also important predictors of mortality (Kabrick et al. 2004). High stand density results in competition for light, water, and nutrients in even-aged stands, and root competition is more severe than crown competition. The root systems of a tree may compete with hundreds of trees, but crowns compete with just a few nearby trees. In fully-stocked stands, competition between individuals will result in elimination of trees less suited to the existing site conditions. This process may happen slowly, abruptly or both, starting in the overstory and then throughout the forest community (Barnes et al. 1980).

White oak grows relatively slow and it can live more than 500 years, black oak seldom lives longer than 200 years. Scarlet oak is also relatively short-lived species compared to white oak (Hicks 1998). At the same age, red oak species are more susceptible to decline compared to white oak species since physiologically old trees are most susceptible to die (Wargo et al. 1983, Hicks 1998, Clatterbuck and Kauffman 2006). For example, a 200 year old red oak is nearing the end of its life, however, a 200 year old white oak has not likely quite reached its physiological mid-life. Crown class can be used to indicate stand susceptibility and it is also a determinant of a tree's ability to recover from defoliation (Johnson et al. 2002). A simple classification of crown class illustrates the results of intense competition in even-aged stands. Crown classes are usually categorized as dominant, codominant, intermediate, or suppressed. "Dominant" trees have crowns extending above the general canopy, and they receive full sunlight from above and some on the sides. "Codominant" trees form the general canopy and they receive full sunlight from above but little to none on the sides. "Intermediate" trees receive some but not full sunlight from above and none from the sides. "Suppressed" trees are fully overtopped by the canopy and they receive no direct sunlight from above or sides (Barnes et al. 1980, Shifley and Brookshire 2000).

***Inciting factors****:* Oak decline is believed to be triggered by drought, which is an extreme and short-term stress to trees (Lawrence et al. 2002). Foliage moisture is more sensitive to the stress of drought. Any stress that leads to reduced foliage moisture or loss of foliage influences stand susceptibility. There is a lag time between drought conditions and the onset of decline (Millers et al.1989). Late spring frost causes tree defoliation which also contributes to oak decline (Law and Gott 1987). Hurricanes and tornadoes damage branches, boles and roots and this may allow entry of disease-causing organisms. Strong gusts of wind during severe weather events may cause similar damage. Declining trees have deteriorating root systems that are more susceptible to windthrow.

***Contributing factors****:* Secondary agents, such as insects and diseases, attack highly stressed and weakened trees, especially in dry environments. Insect attacks are not usually fatal, but epidemics can weaken trees. Two major pests associated with oak decline are the two-lined chestnut borer (*Agrilus bilineatus*) and Armillaria root rot (*Armillaria mellea*) (Wargo et al. 1983). Repeated defoliation by insect and disease attacks on already stressed trees can lead to mortality. Mortality is usually highest two years after heavy insect defoliation. Fungi can produce spots, blisters and blights on the foliage and can be transmitted from stump to sprout. Decay fungi cause cankers, rots, and discoloration of the whole stem and root (Solomon et al. 1980). Fungal spread increases with more available dead or dying root tissues. Damaged trees are susceptible to the infection by sap or heart rots since the wounds are entries for fungi. A known example is oak wilt which is a kind of vascular oak disease caused by fungus that is widespread throughout the eastern United States. It can cause the death of a scarlet oak within a few weeks after the first symptoms appear (Campbell 1965).

**Impacts of timber harvesting on oak decline and mortality**

Ecological succession has two types: primary and secondary (Johnson et al. 2002). Primary succession involves long-term ecosystem changes which may cover thousands of years. Secondary succession involves shorter-term changes that occur after a disturbance. Prescribed silvicultural practices such as timber harvest can be used to create disturbance to direct secondary succession for a desired stand structure and composition. An opening created by disturbances in the forest can increase the available resources in and around the opening. Within the gap, the height growth of pre-established tree reproduction and sub-canopy trees can facilitate the successional replacement of canopy dominants. Differences among tree species in shade tolerance, longevity and growth potential influence how the species composition of the stand will change over time.

Impacts of timber harvest on oak decline and mortality lie in the fact that it regulates intra- and inter-species competition. Competition is a relationship between two species when they are not symbiotic with each other and they occupy the same landscape for the entire life cycle (Barnes et al. 1980, Grubb 1985). The results depend on the susceptibility of a plant to both above- and underground interference, and to its inherent needs for tolerances of light, temperature, water, nutrients, and other site resources. For each individual tree, either the requirement for more for crown and roots growing space or death will result in the changes in forest structure and composition, and subsequently, forest succession. Competition may occur in either even- or uneven-aged stands, and in both the canopy and understory layers.

Silvicutural practices such as thinning can reduce stocking and competition for moisture and nutrients and promote better health and vigor of the remaining trees (Wargo er al. 1983). Forest disturbances can be classified according to their size and impact on stand development. Gap-scale disturbance occurs when a single tree (e.g. single-tree selection) or a small group of trees (e.g. group selection) are lost from the main canopy. The created canopy gaps increase available light and soil moisture to trees within and around the gap. Incomplete stand-scale disturbances, such as group selection and thinning, are larger and more disruptive to the stand compared to gap-scale disturbance. Stand replacement disturbance is the largest and most severe disturbance (e.g. clearcutting) that removes most or all of the overstory to start a new stand. Appropriate practices can improve tree health. Removal of old, mature, weak, and dying trees and maintaining healthy and vigorous trees are important for forests to counteract decline and secondary attacks from contributing factors such as insects and diseases (Shifley 2004).

Besides the positive post-harvesting results such as improving tree health and adjusting stand structure and composition, forest managers are also concerned with potential damage to residual trees caused by harvest entries. Collateral damage includes the inevitable results from changes such as increased stump population and skidding disturbance. Dwyer et al. (2004) reported that accidental damage commonly includes logging damages such as soil disturbance, root damage, bole damage and crown damage. Logging operations may cause soil displacement, compaction, and erosion. Logging damage to roots usually occurs within a distance of 1.0 to 1.5 times of the maximum crown radius of the residual trees. It is nearly unavoidable for residual trees to suffer from different levels of impact of skidding, loading, and hauling activity within that distance. Bole wounds induce a potential degradation to tree health, quality, and the timber value. Tree diameter and distance from the skid trail are two factors that impact the probability of a tree bole to be damaged. Crown damage to the residual trees can be caused during the felling operation. Appropriate planning of the skid trails and well-trained operators are important to minimize impacts of logging damage.

At MOFEP, silviculturists are interested in the impact of canopy openings created by harvesting on not only oak regeneration but also the development of residual oaks. The objective of this study is to identify potential risk factors associated with mortality of oak residuals post-harvest and to examine the effects of four harvesting methods (intermediate cutting, single-tree selection, group selection, and no cut) on the decline and mortality of oak residuals. The answer to the question of "how mortality of overstory residual trees changes in oak forests after harvesting, along with other potential risk factors of oak mortality in upland oak forests" may be used to assess mortality after harvesting based on the current condition of a forest in long-term studies of forest health monitoring.

## Methodology

In this chapter, study area, study design and data collection procedures are the same as delineated in Chapter II. Three management regimes were applied: control, even-aged and uneven-aged management. Each of the three treatment regimes was replicated on three sites. In this study, survival analysis focused on overstory trees, that is, trees with diameter at breast height (dbh) of at least 11.4 cm (4.5in). Tree characteristics of diameter, species, crown class (dominant, codominant, intermediate, and suppressed), and status (live, dead, blown-down, den, and cut) of each mature tree were collected on the 0.2-ha circular plot.

### Data Analysis

Harvesting was conducted in 1996. There were a total of 30,058 permanently tagged pre-harvest live trees among the four harvesting methods that were used in this survival analysis. Post-harvest fates of those tagged trees were continuously collected in the inventory years of 1998, 2002, and 2006. Logistic regression and survival analysis were used in data analysis. In this study, the analysis of effects of the four harvesting methods on mortality of oak residuals was focused on four major oak species: white oak, black oak, scarlet oak and post oak.

*Logistic regression analysis:* Logistic regression can be used for regression analysis of dichotomous (binary) dependant variables. In this study, it was used to model the relationship between the tree mortality that occurred by 2006 and risk factors that cause tree mortality after harvesting. For *k* explanatory variables and *i* = 1, 2, … n individual trees, the Logit model (a.k.a. log-odds or logistic transformation) is

$$\log[\frac{p_i}{1-p_i}] = \beta_0 + \beta_1 x_{\mathrm{i1}} + \beta_2 x_{\mathrm{i2}} + ... + \beta_{\mathrm{k}} x_{\mathrm{ik}} \qquad (3\text{-}1)$$

where $p_i$ is the dependant variable, the probability that a tree die in the inventory year 2006.

$x_{\mathrm{i}}, x_2, \ldots x_{\mathrm{k}}$ are potential risk factors, such as harvesting, species, ELT, crown class, treatment, basal area in larger trees (BAL) and diameter.

$\beta_0, \beta_1 \ldots, \beta_k$ are unknown regression coefficients.

By solving the logit equation (3-1), $p_i$ is represented as:

$$p_i = \frac{1}{1 + \exp[-(\beta_0 + \beta_1 x_{\mathrm{i1}} + \beta_2 x_{\mathrm{i2}} + \ldots + \beta_{\mathrm{k}} x_{\mathrm{ik}})]} \tag{3-2}$$

So the logistic function $f(z)$ can be defined as,

$$f(z) = \frac{1}{1 + e^{-z}} \tag{3-3}$$

where $z = \beta_0 + \beta_1 x_{\mathrm{i1}} + \beta_2 x_{\mathrm{i2}} + \ldots + \beta_{\mathrm{k}} x_{\mathrm{ik}}$

SAS procedure of PROC LOGISTIC (SAS version 9.2, SAS institute, Cary, NC) were used. Coefficients were estimated by maximum likelihood (MLE). The hypothesis testing for the significance of coefficients was completed using the Wald Test:

$$Z^2 = \left( \frac{\hat{\beta}}{s(\hat{\beta})} \right)^2 \tag{3-4}$$

$\chi^2$ goodness-of-fit test (Hosmer-Lemeshow) statistics will be used to assess model fit. Odds ratio will also be calculated.

*Survival analysis:* Conventional statistical methods have difficulty handling censoring data and time-dependent covariates. The survey data of the mortality of oak residuals is right-censored data which means the failure time (or the survival time) of the residuals was observed to be either exactly or greater than a censoring time. A survival analysis procedure is more accurate for studying this kind of event. SAS procedure of PROC LIFETEST (SAS version 9.2, SAS institute, Cary, NC) was applied to model the distribution of survival time with a set of covariants (Allison 1995, Cantor 2003).

PROC LIFETEST produces estimates of survivor functions and comparison of survival curves. Survival Distribution Function (SDF), also called survivor function, is used to describe the lifetimes of populations of interest. The SDF evaluated at *t*, the probability that an experimental unit from the population will have a lifetime exceeding *t*, that is

$$S(t) = \Pr(T > t) \tag{3-6}$$

where $S(t)$ denotes the survivor function and T is the lifetime of a randomly selected experiment unit. The product-limit (Kaplan-Meier) method is used for testing the null hypothesis that the survivor functions are identical for two or more groups (strata). Suppose there are *k* distinct event times, $t_1 < t_2 < ... < t_k$. At each time $t_j$, there are $n_j$ individuals who are said to be at risk of an event; they have not experienced an event nor have they been censored prior to time $t_j$ . If any cases are censored at exactly $t_j$ , they are also considered to be at risk $t_j$. Let $d_j$ be the number of individuals who die at time $t_j$, the Kaplan-Meier estimator is defined as

$$\hat{S}(t) = \prod_{j:t_j \le t} (1 - \frac{d_j}{n_j}) \tag{3-7}$$

for $t_1 \le t \le t_k$ .For a given time *t*, this formula takes all the event times that are less than or equal to *t*. For $t < t_1$, let $\hat{S}(t) = 1$. For $t > t_k$, let $\hat{S}(t) = 0$ . Log-rank test is commonly used (Cantor 2003) for testing the homogeneity of survival functions across strata.

The relationship between survival rate and mortality is, survival rate=1- mortality.

## Results

Four major oak species on the MOFEP sites were used in this study. Two tree-level data analysis methods were employed in the study, logistic regression and survival analysis. The following section reports the results generated by these two methods.

**Risk factors**

Partial association of risk factors and the corresponding odds ratios for each species were estimated. A total of 30,058 residual trees were used (Table 3.1). Potential risk factors such as species, crown class, ELT, treatment, diameter, and BAL were estimated for each species (Table 3.2). The final model included only factors significant to mortality. These factors vary by species.

Table 3.1 Numbers of trees tracked in each group by species, ELT and crown class

| | Dry sites | | | | Mesic sites | | | |
|---|---|---|---|---|---|---|---|---|
| Crown class* | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| White oak | 368 | 1505 | 2269 | 907 | 419 | 1887 | 2757 | 1137 |
| Black oak | 1097 | 2917 | 1101 | 158 | 708 | 1633 | 552 | 70 |
| Scarlet oak | 998 | 2092 | 1204 | 218 | 830 | 1736 | 713 | 132 |
| Post oak | 168 | 631 | 538 | 192 | 145 | 515 | 352 | 109 |

* Note: The numbers of 1, 2, 3 and 4 represent Dominant, Codominant, Intermediate, and Suppressed crown class, respectively.

Table 3.2 Partial association of risk factors for oak mortality in year 2006 at MOFEP

| Species | Number of dead/live trees | Risk factor | Estimated Coefficients (S.E.) | Odds ratio and (95% CI) | Hosmer-Lemeshow goodness-of-fit (p>Chi-square) |
|---|---|---|---|---|---|
| White oak | 864/10385 | No cut | 0 | Reference class | 0.0012 |
| | | Intermediate cut | 0.2893 (0.1751) | 0.749 ( 0.531-1.055) | |
| | | Single-tree selection | 0.4645 (0.0986) | 1.591 (1.312-1.931) | |
| | | Group selection | -0.1465 (0.1931) | 0.864 (0.592-1.261) | |
| | | Dry sites | 0 | Reference class | |
| | | Mesic sites | 0.5310 (0.0764) | 1.701 (1.464-1.975) | |
| | | Dominant | 0 | Reference class | |
| | | Codominant | -0.2351 (0.2108) | 0.790 (0.523-1.195) | |
| | | Intermediate | 0.7319 (0.1940) | 2.079( 1.421-3.041) | |
| | | Suppressed | 1.6032 (0.1959) | 4.969 (3.384 -7.295) | |
| Black oak | 2350/5886 | Dry sites | 0 | Reference class | 0.0883 |
| | | Mesic sites | 0.1688 ( 0.0539) | 1.184 (1.065- 1.316) | |
| | | Dominant | 0 | Reference class | |
| | | Codominant | 0.4102 (0.0891 ) | 1.507 (1.266 - 1.795) | |
| | | Intermediate | 1.6599 ( 0.1174) | 5.259 (4.178 - 6.619) | |
| | | Suppressed | 2.3506 ( 0.1800 ) | 10.492 (7.372 - 14.932) | |
| | | Diameter(1 cm) | 0.0774 ( 0.00984 ) | 1.080 (1.060- 1.101) | |
| | | Basal area in larger trees ($1m^2$) | 0.0972 ( 0.00718 ) | 1.102 (1.087 -1.118) | |
| Scarlet oak | 1667/6256 | No cut | 0 | Reference class | 0.0773 |
| | | Intermediate cut | -0.2169 (0.1600) | 0.805 (0.588- 1.101) | |
| | | Single-tree selection | 0.2385 (0.0977 ) | 1.269 (1.048- 1.537) | |
| | | Group selection | 0.3323 (0.1317) | 1.394 (1.077-1.805) | |
| | | Dominant | 0 | Reference class | |
| | | Codominant | 0.2028 (0.1046 ) | 1.225 (0.998-1.503) | |
| | | Intermediate | 1.6489 (0.1332) | 5.201 (4.006-6.753) | |
| | | Suppressed | 2.6210 (0.1709 ) | 13.750 (9.837 -19.219) | |
| | | Diameter(1 cm) | 0.1365 (0.0115) | 1.146 (1.121 -1.172) | |
| | | Basal area in larger trees ($1m^2$) | 0.1158 (0.00901) | 1.123 (1.103- 1.143) | |
| Post oak | 334/2316 | Dry sites | 0 | Reference class | 0.4206 |
| | | Mesic sites | 0.4630 (0.1230) | 1.589 (1.249- 2.022) | |
| | | Dominant | 0 | Reference class | |
| | | Codominant | 0.1219 (0.2613) | 1.130 (0.677 -1.885) | |
| | | Intermediate | 0.6535 (0.2747) | 1.922 (1.122 -3.293) | |
| | | Suppressed | 1.4286 (0.3005 ) | 4.173 (2.315-7.520) | |
| | | Basal area in larger trees ($1m^2$) | 0.0433 (0.0151) | 1.044 (1.014-1.076) | |

The factor ELT was not significant for scarlet oak. Results indicated that for white oak, the odds ratio of mesic sites to dry sites was the highest (1.7) compare to scarlet oak and black oak.

Diameter and BAL had significant effects on the mortality of scarlet oak and black oak. Results showed the odds ratio of diameter of scarlet oak is 1.146, which is greater than that of black oak (1.080). This indicated that scarlet oak was more likely to die than black oak with each 1 cm increase of diameter. For white oak, diameter and BAL were not significant for mortality. For post oak, BAL contributed little with an odds ratio 1.044 which means for each 1 $m^2$ increase in BAL, mortality increased by a ratio of 1.044. The capability of tree crowns to capture light increases a tree's survival rate. Overall, trees with suppressed or intermediate crown classes had higher mortality than trees with dominant or codominant crown classes. For white oak, scarlet oak and post oak, there was no significant difference between dominant and codominant crown classes with respect to mortality. For black oak and scarlet oak, the odds ratio of suppressed crown class to dominant crown class was over 10. This was much higher than that of white oaks, which is less than 5. Harvesting treatment was a significant mortality factor for white oak and scarlet oak only. For white oak, only single-tree selection induced a significantly higher mortality rate than no harvesting. For scarlet oak, trees under single-tree selection and group selection treatments had an increased chance of dying compared to no harvesting; group selection produced higher mortality than single-tree selection. ELT had no significant effect on the mortality of scarlet oak residuals. The Hosmer-Lemeshow goodness-of-fit test indicated significant lack of fit for the model of white oak, indicating that more factors should be considered for this model. For other species, there was no lack of fit.

**Survival rate**

Overall, by 2006, results indicated that red oaks had higher average mortality (0.326) than that of white oaks (0.0998) (Figures 3.1-3.8). Black oak had a higher mortality rate than scarlet oak, 0.3838 and 0.2681, respectively. There is a high correlation between oak mortality and crown class. Trees with intermediate or suppressed crown class exhibited much higher mortality than that of dominant or codominant crown classes. In white oaks, the average morality of intermediate or suppressed trees was 0.14, which is higher than that of dominant or codominant trees (0.06). In red oaks, the average morality rates of intermediate or suppressed trees and dominant or codominant trees were 0.55 and 0.15, respectively.

On dry sites, none of the log-rank tests showed significant treatment difference for trees with dominant crowns. For white oak, the log-rank tests for homogeneity indicate strong evidence of significant differences among the survival curves for the four treatments ($P<0.01$) in the groups of trees with codominant, intermediate and suppressed crowns (Figure 3.1). Compared to no harvesting, single-tree selection showed relatively high mortality in these three groups, especially in the suppressed white oak around. Intermediate cutting caused the least mortality in suppressed trees. No harvesting produced the least mortality in codominant and intermediate trees. By 2006, group selection and no harvesting exhibited similar mortality in white oak with intermediate and suppressed crowns. For post oak, none of the strata tests indicated significant differences.

On dry sites, red oak species strata test indicated significant differences in black oak and scarlet oak trees with intermediate crowns, codominant trees of black oak, and suppressed trees of scarlet oak (Figures 3.3 and 3.5). Compared to no harvesting, the intermediate cutting resulted in the lowest mortality in all red oaks except the dominant ones. Group selection resulted in much higher mortality in red oak trees with intermediate or suppressed crown.

On the mesic sites, only two groups demonstrated significant differences among the survival curves for the four treatments: the group of white oak with suppressed crowns and the group of black oak with dominant crowns. For white oak, group selection produced the highest survival rate and no harvesting resulted in the lowest (Figure 3.2), but for black oak, these results were reversed (Figure 3.4).

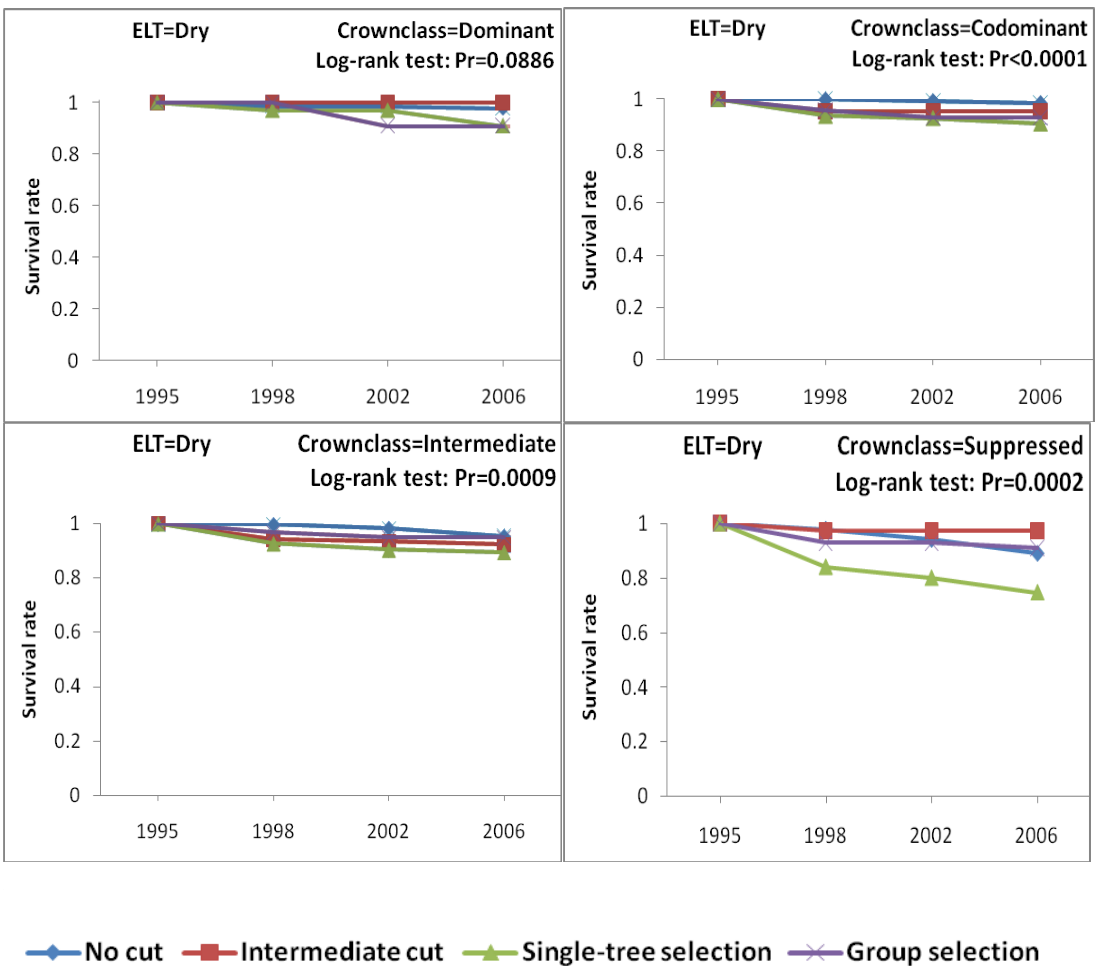


Figure 3.1 Survival of white oak under various harvesting methods on dry sites

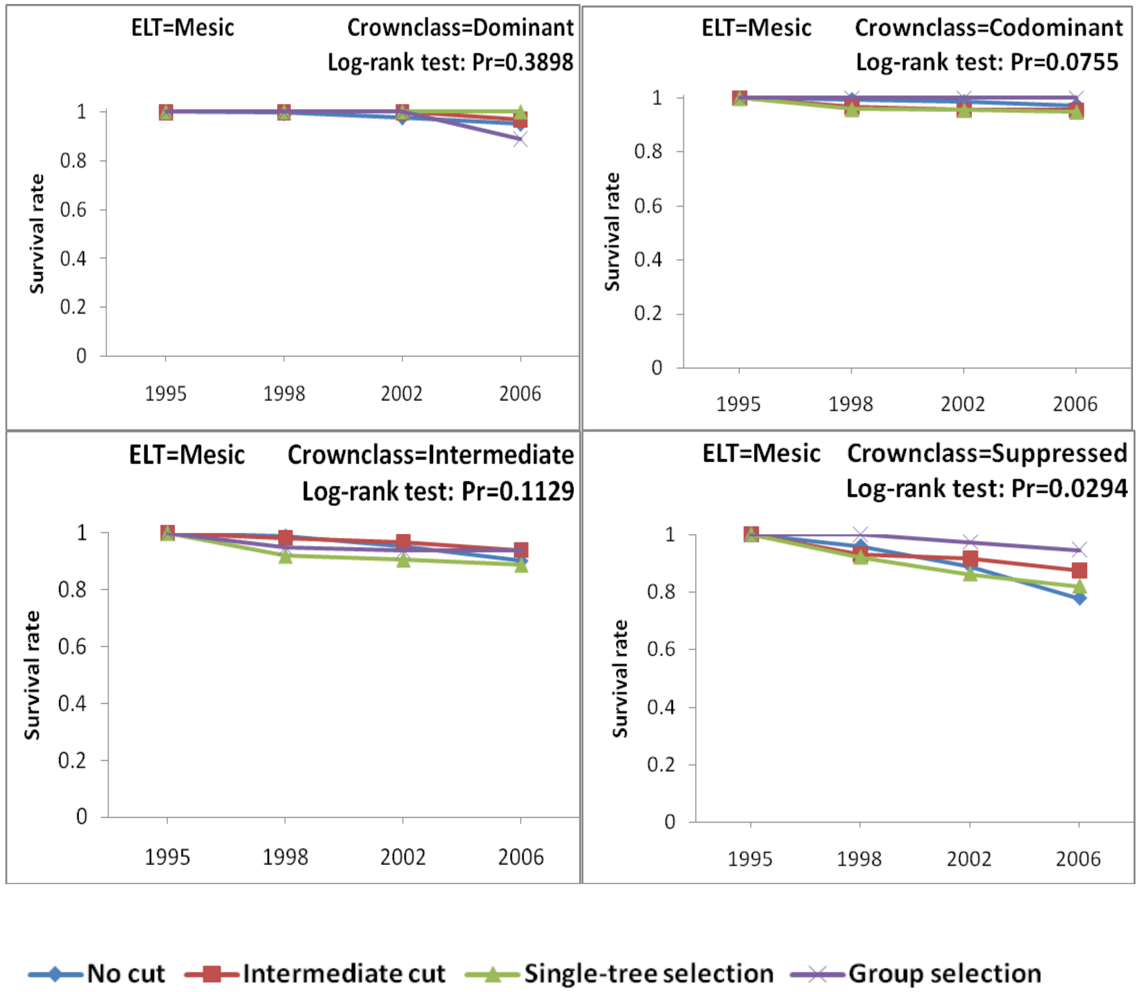


Figure 3.2 Survival of white oak under various harvesting methods on mesic sites

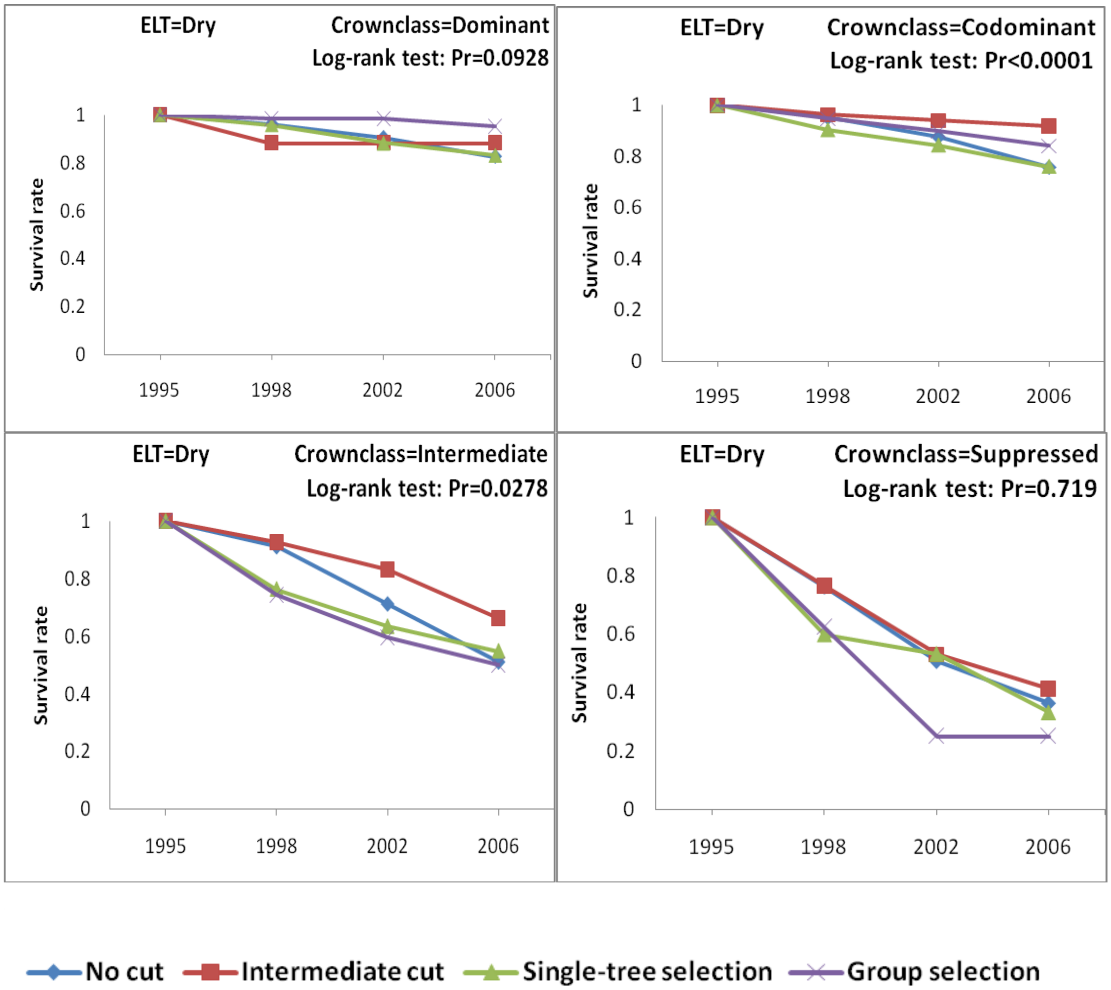


Figure 3.3 Survival of black oak under various harvesting methods on dry sites

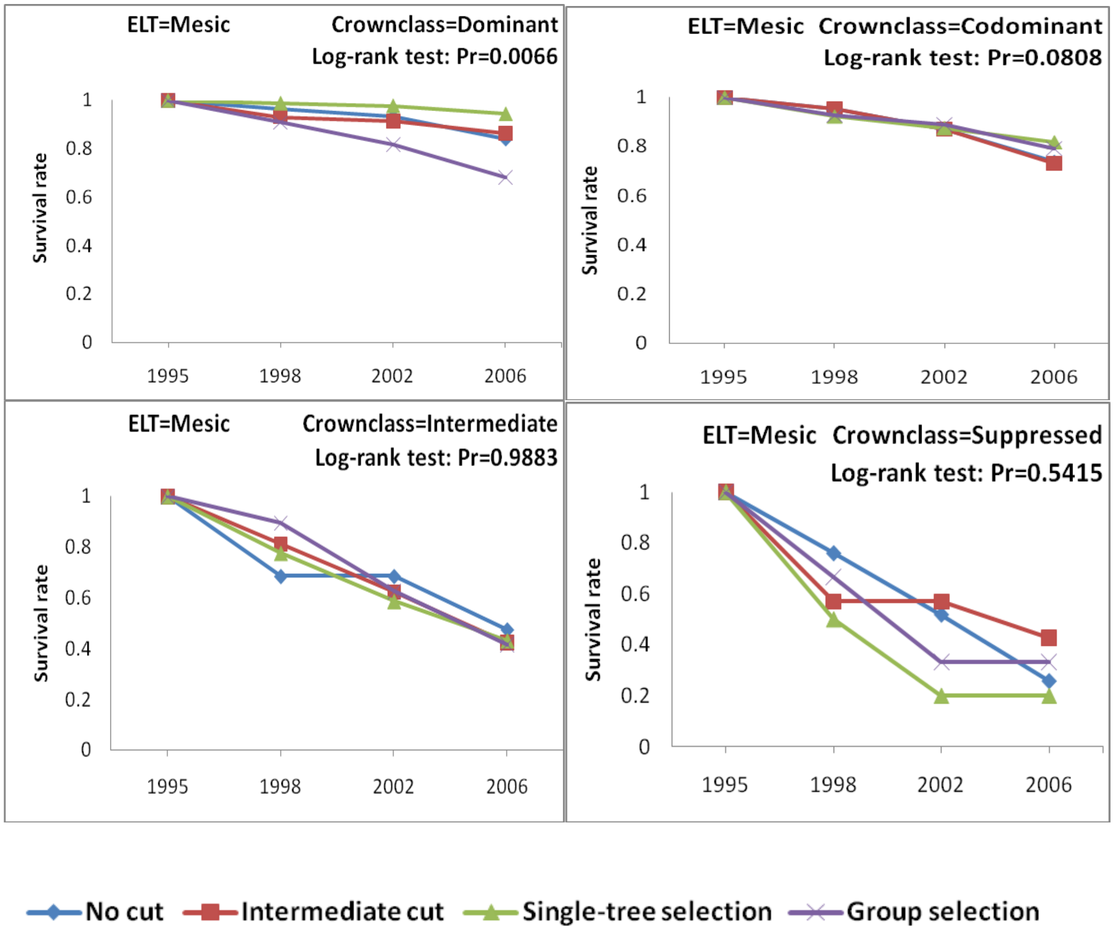


Figure 3.4 Survival of black oak under various harvesting methods on mesic sites

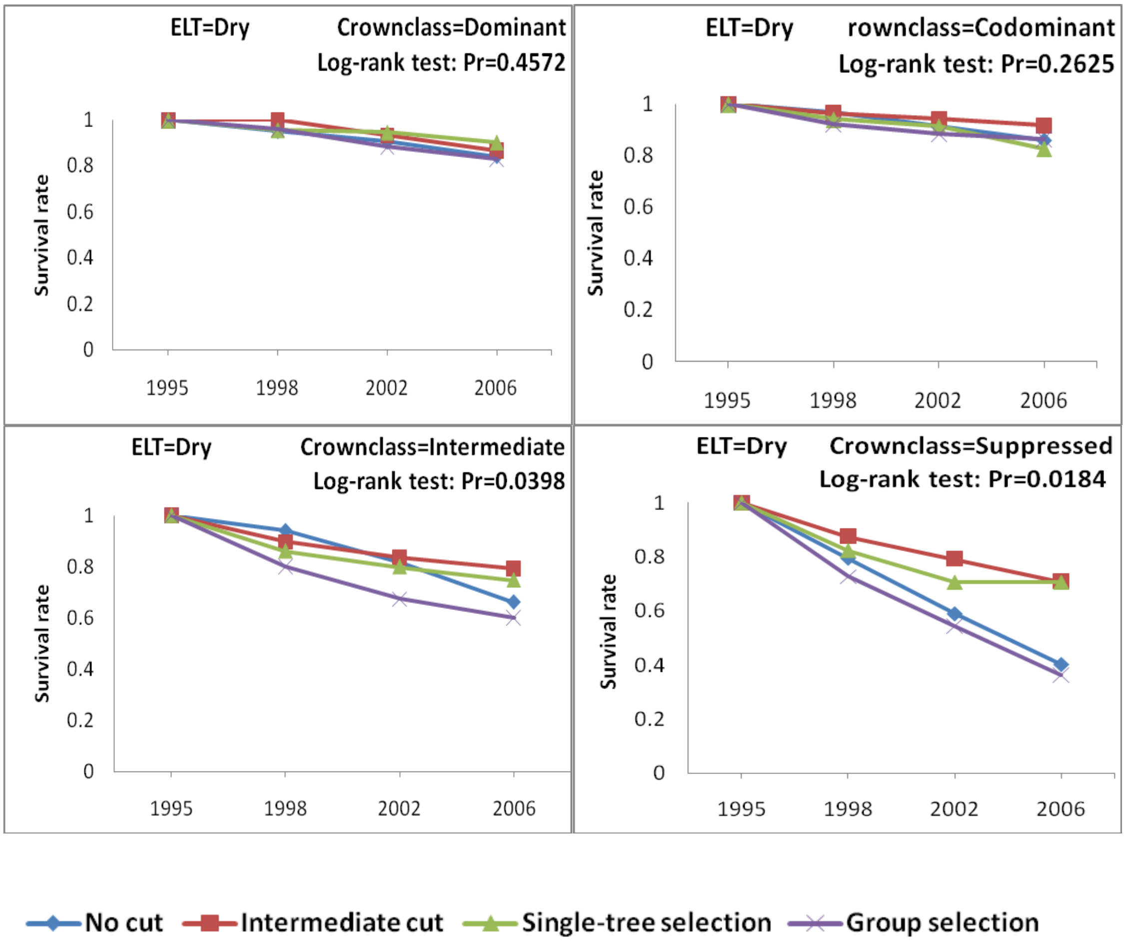


Figure 3.5 Survival of scarlet oak under various harvesting methods on dry sites

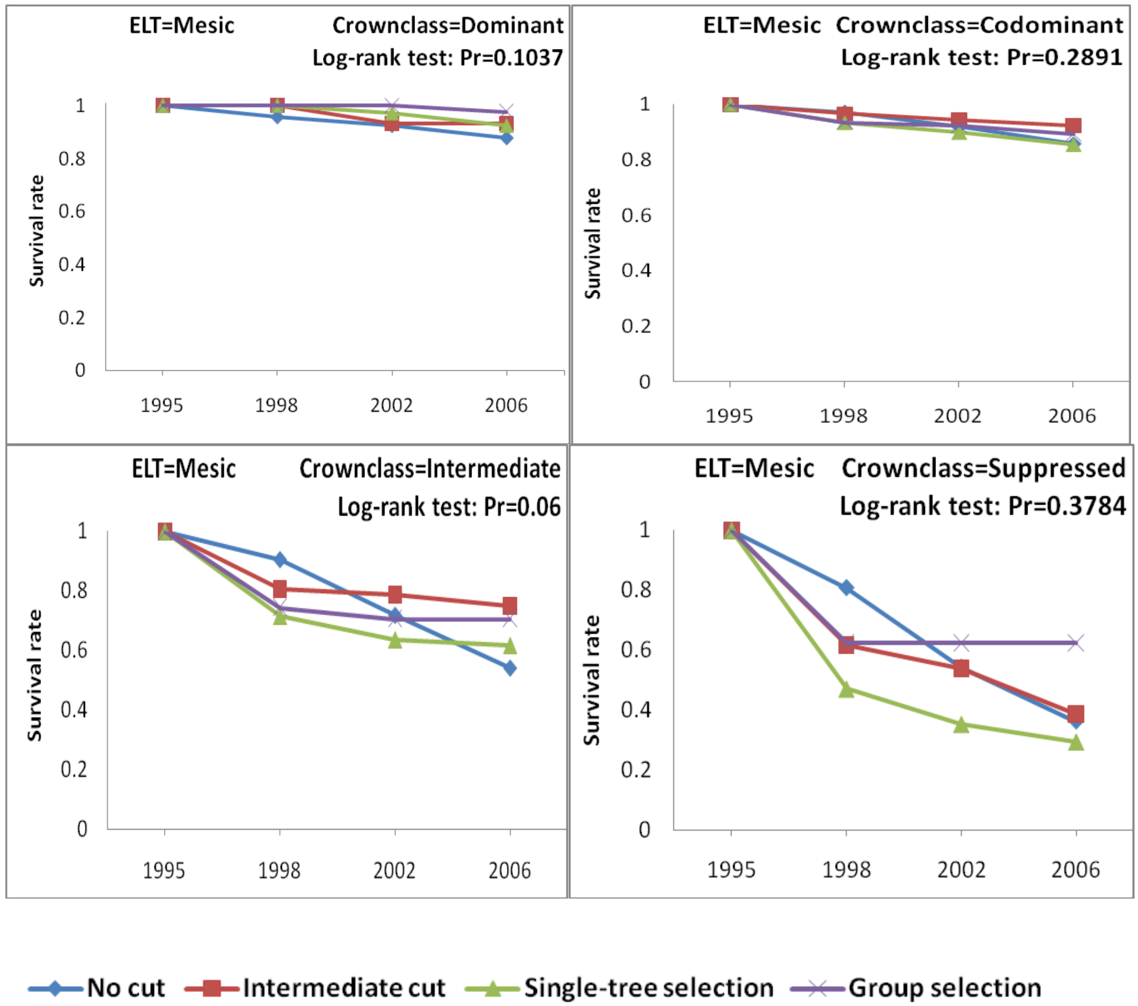


Figure 3.6 Survival of scarlet oak under various harvesting methods on mesic sites

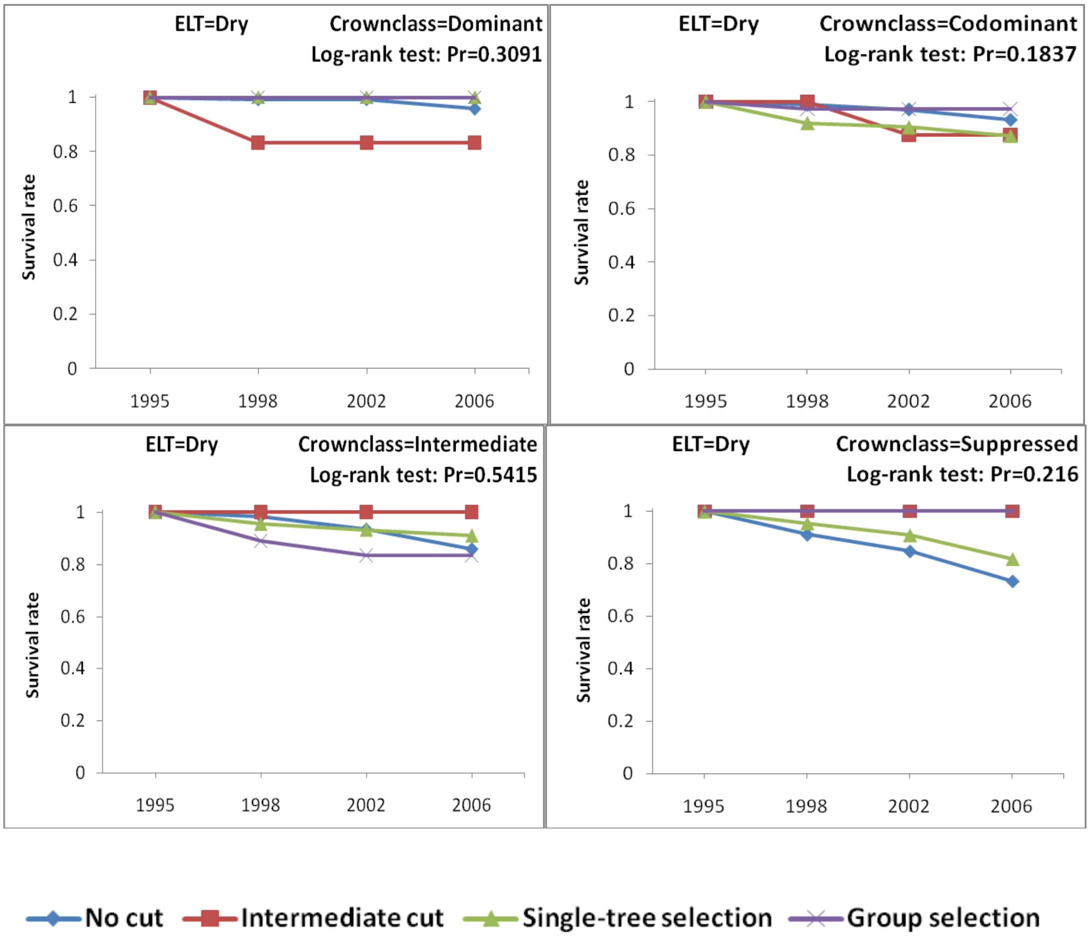


Figure 3.7 Survival of post oak under various harvesting methods on dry sites

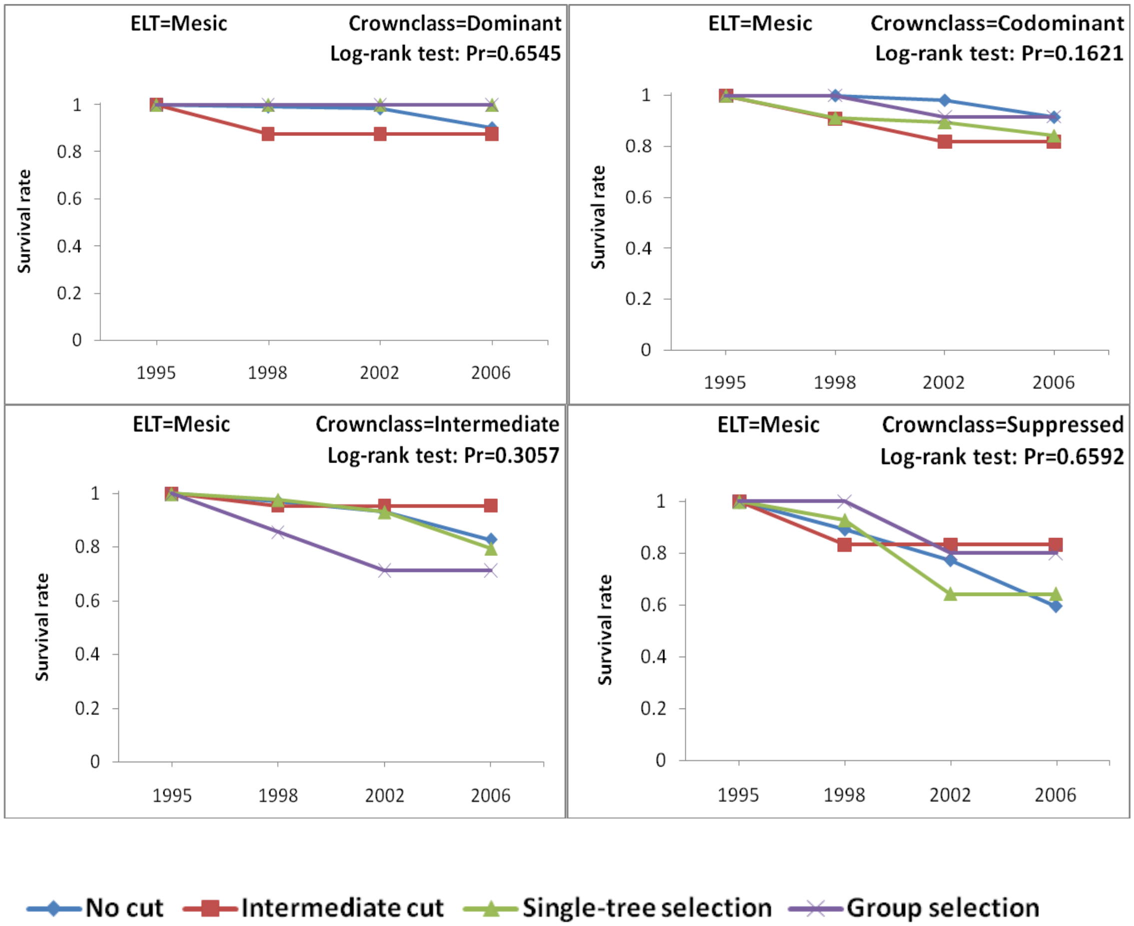


Figure 3.8 Survival of post oak under various harvesting methods on mesic sites

# Discussion

## Response to risk factors

*Diameter and BAL:* Overstocking of mature trees in a stand results in reduced ability to overcome stress and recover growth. Excessive basal area exacerbates moisture stress especially during periods of drought (Chadwell Buckley 2003).White oak's longevity and greater drought and shade tolerance provide it a competitive advantage over red oaks. This may explain why the factors of diameter and BAL did not show significant impact on white oak mortality (Table 3.2). BAL was significant to red oaks because they are shade-intolerant species. Red oaks are relatively short-lived species as compared to white oaks. Vigor of regeneration is typically indicated by tree height and diameter growth. Tree diameter growth usually slows down before decline symptoms appear (Stringer 2006). This may explain why diameter is a significant factor in the mortality of red oaks. This result is consistent with a previous study (Shifley et al. 2006).

*ELT:* Oaks have a conservative growth strategy. During the early years, oaks invest a significant amount of energy to develop a taproot and to maintain a high root : shoot ratio which makes them drought resistant and competitive on dry-mesic or xeric sites (Dickson 1991). On poor sites, oaks have an advantage over many other species. But on good sites, oak seedlings are easily overtopped by fast-growing competitors. This is especially true with regard to white oak reproduction (Crow 1988). It is also one of the reasons why oaks are often found in low-quality sites (Hicks 1998).

In this study, ELT did not show a significant effect on mortality for scarlet oak, but for other species such as white oak, black oak, and post oak, it contributed to the mortality of residuals (Table 3.2). This result is similar to those found in previous studies. Many other studies have shown that oak decline is a serious problem on sites with lower productivity especially in red oak group (Starkey et al. 2004, Clatterbuck and Kauffman 2006), but site condition does not have a significant effect on red oaks mortality rate, and not all xeric sites display high levels of damage (Shifley et al. 2006, Heitzman et al. 2007, Kabrick et al. 2008). Kabrick et al. (2008) indicated that red oaks were more abundant on droughty and nutrient-poor sites. Stand factors of species composition, tree age and stocking are more important determinants of oak decline than site factors of topography, aspect, slope, land form and ELT.  Scarlet oak does occur on better sites (Hicks 1998), and its capability to grow faster than most other oaks and hickories enables it to stay ahead of competitors.

*Crown class:* Crown class can be used to evaluate an individual tree's ability to compete for light, water, and nutrients.  Trees in lower crown classes are shaded by the dominant and codominant trees, and are more likely to die (self thinning) from competition (Table 3.2). Silviculturists use crown classes as a basis for judging the vigor of the stand and for conducting thinning or other cultural operations (Barnes et al. 1980). The mortality of red oaks is more sensitive to crown class than white oaks (Table 3.2), especially for suppressed red oaks. This may be explained by the lower shade tolerance of red oaks than white oaks. This result is consistent with Shifley et al. (2006).

**Response to harvesting treatments**

Competition among trees for light, water, and nutrients is the primary reason for tree mortality in a stand (Barnes et al. 1980). Control of stand density is very important in forest management since increasing density will cause a decrease in diameter growth. Silvicutural practices (e.g. thinning) can reduce competition for moisture and nutrients and promote health and vigor in a stand (Wargo et al. 1983). While trees may develop and respond quite differently according to the combination of genetic and environmental factors (Barnes et al. 1980), some grow rapidly with big, well-formed crowns, some grow slowly with restricted crowns, and others will be gradually overtopped.

Single-tree selection is a planned disturbance to maintain a desired stand age and size structure, species composition and stocking by targeting individual trees (Bruhn et al. 2002). The size of a canopy gap depends on the crown areas of the single tree harvested. Harvesting reduces the rate of natural mortality from self-thinning, increases the growth rate of individual trees in the residual stand and accelerates the ingrowth of reproduction into the overstory. This treatment also reduces less desirable competitors by selectively cutting smaller trees from the midstory and removing some larger trees.

However, selection harvest methods require multiple entries which may negatively impact tree quality of the residuals and increase the potential for future diseases and insect infestations (Dwyer et al. 2004). Logging damages reduce timber value. In this research, mean number of bole wounds per tree was highest in single-tree selection areas. For white oak on dry sites, single-tree selection resulted in the highest mortality in suppressed trees (Figure 3.1). Damaged trees are subject to infection because the wound is an entry point for fungi. Dead or dying root tissues and down woody material from harvesting are food sources for these fungi which may cause root disease, defoliation, and oak wilt (Bruhn et al. 2002, Johnson et al. 2002).

Group selection creates openings with diameters equal to 1-2 times the height of overstory trees (Smith 1986) depending on location, aspect, and the management purpose of improving stand quality. Available light received in the gap will decrease with time because of crown expansion from residuals around the opening. Group selection produced slightly higher mortality in red oaks compared to no harvesting (Figures 3.3, 3.5, Table 3.2). This result is consistent with Starkey and Oak (1989) that reported selection silvicutural treatments accelerated oak mortality related to oak decline, especially in the stands predominated by red oak species. The slightly higher mortality may be a result of edge effect which is the impact of timber harvesting and openings on oak decline in the surrounding forest. Small openings create a large ratio of perimeter to open area. Trees on the edge of openings may be predisposed to oak decline because of stresses from a sudden crown exposure, harvesting machinery damage to the root system and associated pathogenic effects (Oak et al. 1996, Johnson et al. 2002). A sudden crown exposure will change microclimatic conditions which may cause temporary stresses on trees with increased sunlight, soil temperatures, and wind and winter injury. In return, these stresses may reduce the capability of trees to counteract pathogens (e.g. Armillaria root disease) before they can benefit from thinning (Wargo and Harrington 1991, Johnson et al. 2002). This may explain why group selection resulted in a higher mortality rate for the residual intermediate and suppressed black oak and scarlet oak trees versus natural mortality without harvesting, even though they are shade-intolerant (Figures 3.3, 3.5). However, intermediate cuttings reduced the mortality for these two groups.

Intermediate cuttings are designed to improve the growth, quality, vigor or composition of trees in a stand (Johnson et al. 2002). For the purpose of reducing the impact of insects and diseases such as gypsy moth, oak decline or oak wilt, this method is useful and efficient. When the MOFEP study was initiated, the forests were second growth and fully stocked (Gingrich 1967, Kabrick et al. 2008) and most trees were free from manipulation for at least 40 year (less than 5 percent of area disturbed). Mature black oak and scarlet oak are more vulnerable than white oaks to environmental stress caused by drought. Red oak species in this area had high mortality in overstory trees, and low reproduction success thereby creating unstable long-term sustainability (Heitzman 2003). Intermediate cuts benefit red oak residuals by reducing the mortality to a much greater degree than other treatments. For suppressed white oak, this method is also a good option for reducing mortality (Figure 3.1).

## Summary

Silvicultural treatments can be considered as prescribed disturbances with the purpose of controlling future stand composition and structure (Johnson et al. 2002). Silvicultural practices, which are the best known tool for managing oak decline through prevention and maintaining healthy and vigorous trees, were designed in this study to help species to adapt to site conditions and to reduce the impact of drought.

Timber harvesting has both positive and negative effects on oak residuals. Harvesting reduces competition among trees, but some methods exacerbate mortality of residuals. Other risk factors such as crown class, ELT, diameters and BAL should also be considered. Among all the silvicultural methods, single-tree selection is the least economically efficient because multi-entries and small volume removal per acre increase operation costs. Single-tree selection did not resulted in reduced mortality. Group selection provided results similar to no harvesting, but this method may reduce the value of oaks by epicormic branching and associated bole degradation caused by edge effects around openings (Smith 1980, Johnson et al. 2002). Intermediate cutting resulted in the best response by residuals of red oak.

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# Chapter IV

# CONCLUSIONS

In this study, the effects of timber harvesting on both oak regeneration and mortality of oak residuals in the Missouri Ozarks were investigated using the sixteen-year monitoring data from the Missouri Ozark Forest Ecosystem Project (MOFEP). Intermediate cutting, single-tree selection, and group selection improved the abundance of oak reproduction in size one which consolidated the structural stability in the reproduction population. Clearcutting was the only method that significantly increased the total reproduction density and developed seedlings into the larger sizes which provided a significant oak component for future stands. Group selection harvest showed potential to develop oak into future stands. Even-aged management increased the compositional proportion of black oak reproduction. Harvesting decreased the relative proportion of white oak on the study sites.

Oak mortality was associated with a set of factors including timber harvesting, crown class, ELT, diameters and BAL. Single-tree selection exacerbated the mortality of oak residuals. Group selection was comparable to the no harvesting treatment in oak mortality, but on the other hand, it might reduce the timber value because of the increased epicormic branching. Intermediate cutting increased the survival rate of red oak residuals compared to no harvesting.

This research suggested that timber harvesting affected stand composition and structure of oak regeneration and impacted mortality of overstory residuals. Clearcutting significantly improved the density of oak reproduction, but it created aesthetic problems if applied at the large scale. Uneven-aged timber harvesting improved understory regeneration but it produced mixed results in overstory residual tree mortality. A longer period of time is needed to evaluate the uneven-aged timber management (group and single-tree selection) effects.  Well-designed silvicultural practices would likely help mitigate oak decline-induced mortality and increase understory oak reproduction.